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Using A Quality Based Analytic Hierarchy Process To Do Decision-making Analysis In Transportation

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USING A QUALITY BASED ANALYTIC HIERARCHY PROCESS TO DO

DECISION-MAKING ANALYSIS IN TRANSPORTATION

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USING A QUALITY BASED AHP TO DO DECISION-MAKING ANALYSIS IN TRANSPORTATION

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The automated identification technology, Radio Frequency Identification (RFID), provides the potential to reduce costs in the transportation operations. Local Department of Transportation (DOT) offices have to carefully consider technologies such as RFID when considering their use for operation such as Right of Way (ROW) property control. ROW operations require strategic planning in that inventory and access rights can be contestable in a myriad of situations. This research investigates the comprehensive impacts of using RFID systems for ROW inventory tracking. We utilize the House of Quality as a means to integrating strategic shareholders needs and their impact on the measurement of the systems usefulness with respect to the RFID systems reliability performance. Multiple RFID systems reliability performance was measured in the harsh ROW environments. We introduced a model that takes both the shareholder requirements and the RFID reliability to demonstrate a multiple decision approach based upon Analytic Hierarchy Process (AHP) to which system provide the best value for improving operational effectiveness.

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Table of Contents

ACKNOWLEDGEMENTS ii

List of Figures v

List of Tables v

Chapter 1 Introduction 1

Chapter 2 Background 5

2.1 RFID Technology 5

2.2 Analytic Hierarchy Process (AHP) 10

2.3 Combination Application of AHP and QFD 12

2.4 Quality Function Deployment (QFD) 14

2.5 The Economic Analysis 16

Chapter 3 Rationale 19

Chapter 4 Methodology 20

4.1 Procedure of the Approach 20

4.2 Rationale 21

4.2.1 Quality Function Deployment 21

4.2.2 Analytic Hierarchy Process 25

4.2.3 Benefit Evaluation of the RFID Systems Implementation 28

4.3 Data Collection 30

4.4 Analysis Plan 32

4.4.1 Quality Function Deployment Analysis 32

4.4.2 Benefit Evaluation Analysis 35

4.4.3 Analytic Hierarchy Process Analysis 40

Chapter 5 Results 45

5.1 Quality Function Deployment 45

5.1.1 Analysis of Customer Requirements 46

5.1.2 Analysis of Technical Requirements 47

5.2 The Basic Quality Based Analytic Hierarchy Process 48

5.3 Quality Based AHP with Boundaries 52

5.4 AHP with Uncertainties 53

5.5 Comparison of Quality Based AHP with Economic Analysis 58
5.5.1 Decision Tree Analysis 58
5.5.2 The Real Option Analysis 59
Chapter 6 Discussion 61
6.1 Possible QAHP approach I 61
6.2 Possible QAHP approach II 64
6.3 Possible QAHP approach III 65
6.4 Limitations 65
6.5 Conclusions 66
Chapter 7 Contribution to the body of knowledge 70
REFERENCES 71
APPENDICE 81
Appendix A: Acronyms Table 81
Appendix B: Explanation of technical requirements in Quality Function Deployment (QFD) 82
Appendix C: Structure of the basic Quality based Analytic Hierarchy Process (QAHP) 83
Appendix D: The Original Matrix for basic QAHP structure 84
Appendix E: Structure of the possible QAHP II 89
Appendix F: Structure of the possible QAHP III 90

List of Figures

Figure 1 Structure of the rfid system (Finkelzeller, 2003)....................................6
Figure 2 Approach for the research..20
Figure 3 General house of quality structure..22
Figure 4 Sample analytic hierarchy diagram 27
Figure 5 Stages for analysis 29
Figure 6 Decision tree as sample 29
Figure 7 Example of the qfd diagram 33
Figure 8 Binominal tree approach for early exercise decision.............................38
Figure 9 House of quality for all stakeholders...45
Figure 10 Decision tree developed for project...55

List of Tables

Table 1 Studies in Combination of AHP and QFD..14
Table 2 Trans-quantitative Scores...26
Table 3 Random index 42
Table 4 Final Evaluation from the HOQ..48
Table 5 Scores Utilized to Find the Pairwise Scores in the AHP 49
Table 6 Pairwise Scores of Customer Requirements 49
Table 7 Weight Modulus of the Customer Requirements (CRW_i).......................50
Table 8 Weights of Technical Requirements (TRW_j) 51
Table 9 Performance of the Alternatives 51
Table 10 Weight Modulus of Alternatives (AlW_l) 52
Table 11 the Consistency Analysis 52
Table 12 Weight Modulus with Boundaries Utilized 53
Table 13 Initial Costs for Different Types of RFID Systems 54
Table 14 Probabilities of Different Situations in Each Phase 54
Table 15 Benefits of Different RFID Systems...56
Table 16 Weight Modulus of Each Alternative 57
Table 17 Weight Modulus with Boundaries 57
Table 18 Savings of Successful Implementation 58
Table 19 Expected Net Present Values of Different RFID Systems 59
Table 20 Net Present Value (NPV) of the Project...60
Table 21 Pairwise Scores of the Customer Requirements from Approach I 61
Table 22 Weight Modulus CRW_i from Approach I 61
Table 23 Weights of Technical Requirements (TRW_j) from Approach I.............62
Table 24 Weight Modulus of Alternatives (AlW_l) from Approach I 63
Table 25 Summary of Results Obtained from Different Approaches..................67

Chapter 1 Introduction

The Department of Transportation (DOT) in the southwest region of the United Sates manages approximately 1.1 million acres of land that provide right-of-way (ROW) for approximately 80,000 center miles of state-maintained roads. Management of the ROW involves managing and inventorying a large number of facilities within the state, including utility (e.g., gas (liquid or natural), energy, sewer, telecommunications, water) assets, roadway infrastructure (e.g., pavements, bridges, traffic signs), and outdoor advertising facilities. It is a challenge to manage these utilities effectively because a significant proportion of assets are underground.

While data management practices within the utility industry varies, the utility industry has used underground markers for decades to help locate cables, pipes, valves, and other underground assets. These markers emanate radio signals typically in a passive mode within a set range of frequencies. Each type of asset uses a unique frequency for asset differentiation; however, these markers do not store or transmit any identification data, which severely limits the usability of the markers for data collection, inventory and inspection purposes.

To address the limitations of underground markers, pioneering researchers and the utility industry have been exploring the use of radio frequency identification (RFID) technology in utility asset management. RFID technology provides the capability to store a unique identification (ID) number and some basic attribute information. This data can be retrieved wirelessly when the markers detect a radio signal from a remote reader. RFID technology has the potential to offer the DOT a unique opportunity to help optimize the management of utility installations within a state's ROW.

It is fresh to introduce RFID technology to control facilities in ROW. "Every successful company has used data and information to help in its planning processes" (Johnson, 2005). In developing a fresh product, engineers have continuously examined the assembly process and execution history of present products. "They look at field test data, comparing their product to that of their competitor's product" (Johnson, 2005). Also the engineers examine any customer satisfaction concerns that have been found to be present. Condemningly, an excessive amount of this information is often left unfinished. "It is frequently examined as individual data, without comparison to other data that may support or contradict it" (Johnson, 2005). To correct this, a quality initiative known as the House of Quality (HOQ), a form of Quality Function Deployment (QFD), is used. This same thought process can be integrated with Transportation stakeholders.

The key product attributes are necessary to satisfy transportation stakeholder concerns for a RFID based license plate system from both a customer and technical standpoint. A description of the QFD process and a more detailed background of RFID are described in the background section. While the QFD just can give an idea what the product should be and how to improve the current one, it cannot be utilized to select the best alternative directly. Some other methods which may help to do decision also introduces in this approach, such as Analytic Hierarchy Process (AHP) to do multiple decision and Real Option Analysis to do economic decision.

This thesis evaluates six different RFID systems and provides a multiple attributes analysis. The six different types of RFID systems are: active Dash7 system (AD7), three different passive non-standard systems (PNS1, PNS2 and PNS3), and two different passive Gen 2 systems (PG21 and PG22). Dash7 is a type of active tag that works at the frequency of 433 MHZ.

There are three locations for the assets considered in the ROW project, which are above ground, underground deeper than 24 inches, and underground up to 24 inches. Based on experiments, there was only one RFID system being able to be utilized attached on the face of the assets above ground in the required environments, and it was AD7. There were two RFID systems being able to be utilized attached with the assets underground deeper than 24 inches, which were AD7 and PNS1. Obviously, PNS1 was better, since their performances were similar and the price of PNS1 was lower than AD7. All of the six RFID systems can be utilized attached with the assets underground up to 24 inches, and their performances and prices had large differences. It is valuable to evaluate their implementations underground up to 24 inches in ROW project.

This study formulates a multiple decision – making analysis of implementing an RFID system that will be used underground up to 24 inches in ROW. The goal of the decision criteria is to find the best system satisfying the customers' requirements and the technical requirements. It needs a comprehensive consideration to make these multiple decisions.

A good choice to do multiple decisions is the AHP (Canada, 1989). In this process, many factors are considered, and the objective is easier to be realized. Next we describe overall methodology for the approach. Then the specific results are presented for the approach.

Chapter 2 Background

There are the backgrounds of the main technologies and methodologies utilized in this research of the thesis. They include RFID Technology, Analytic Hierarchy Process (AHP), Quality Function Deployment (QFD), the application of combining AHP and QFD, and the economic analysis.

2.1 RFID Technology

Radio Frequency Identification (RFID) technology uses electromagnetic waves to exchange data between a terminal and an object to identify or to track such as a product, animal or person. A standard RFID system should consist of a tag, a reader, air interface, and middleware software shown in Figure 1 (Clampitt 2006). Generally, tags consist of a microchip with an internally attached coiled antenna. The microchip is an integrated circuit for storing and processing information, modulating and demodulating a radio – frequency (RF) signal and other specialized functions. The antenna is for receiving and transmitting the signal. Some types of tags also include batteries, expandable memory, and sensors (Ranky 2006). The reader is an interrogating device that has internal or external antennas that send and receive signals.

There are generally three types of RFID tags: active RFID tags, passive RFID tags and battery assisted passive tags. The active tag contains a battery and can transmit signals autonomously. The passive tag has no battery and requires an external source to provoke signal transmission. The battery assisted passive tag requires an external source to wake up, but has significant higher forward link capability providing great read range (Finkelzeller, 2003).

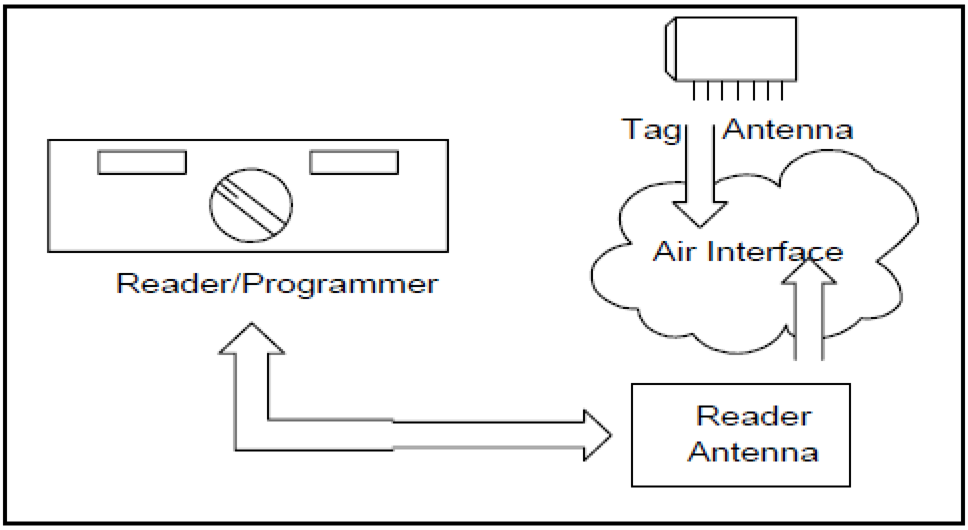

Figure 1 Structure of the rfid system (Finkelzeller, 2003)

Nowadays most systems of 13.56 MHz operate “passive”, without the need for an integrated battery. They have significant advantages on cost, lifetime and the environmental situation. The basic operating principle of passive 13.56 MHz and below 135 KHz RFID systems is to transmit energy and data by inductive coupling. This is exactly the same principle as used in transformers. By changing parameters of the transmitting field (amplitude, frequency or phases), the data transmission from the reader to the tag can be influenced. The return transmission of the tag concerns the load (amplitude and/or phase).

UHF and MW (e.g. 400 – 1000 MHz, 2450 MHz & especially 5.8 – GHz) RFID systems make communication of data and commands by utilizing conventional electromagnetic wave propagation, and battery-less tags also need to be powered by the RFID transponders. The basic operating principle of this RFID system is utilizing propagating radio signals ("E" field transmission) to transmit energy and data.

The ranges are classified as "proximity" (below 100 mm), "medium range" (below 400 mm), "vicinity" (long range – 1.5 m), "far field" (0.5 to 12 meters – 2450 MHz, passive power), and up to 30 meters (active power tags depending on microwave frequency) (Li, 2004). Differences are mainly caused by the output power of this RF – module and by the sensitivity and the selectivity of its receiver. The operating zone of passive inductive RFID system (13.56 MHz and below 135 KHz) is in the "near field" of the read transmission antenna, which results in achievable operating distances of approximately the diameter of the transmission antenna.

RFID originated from radar theories that were discovered by the allied forces during World War II and have been commercially available since the early 1980's (Landt 2001). Some general applications where successful use of the RFID technology has been reported in the literature, such as monitoring oil drill pipe (Strassner, 2003), Florida's Jacksonville International Airport which will have the world's first all – radio frequency identification baggage tracking and identification system (IIE Solutions, 2002), active implantable medical devices (Irnich, 2002); applications in biology (Kampers, 1999; Jansen, 1999; O'Gorman, 1999), and investigation of insect movements (Reynolds, 2002). There are also applications in commerce and clothing (Sakamura, 2001; Hum), RFID technology increasing profits in industry (Callahan, 2002), collision avoidance in mines and in identification system (Ruff, 2001).

RFID is an emerging technology which has been introduced into transportation systems. Over the last two decades, RFID also has been used for a wide variety of applications in transportation such as highway and bridge tolls, livestock tracking, transportation freight tracking and motorcycle manufacturing. Until recently, the technologies were considered expensive and limited, but as the tags, readers, and the associated equipment costs continue to decrease, a growing number of organizations have begun to explore the feasibility of using RFID systems (Jones 2007).

To acquire authentic information, reputable academic databases were used such as Science Direct, World Cat and Web of Science. The literature search was conducted by using keywords such as "RFID", "Radio Frequency Identification", "RFID in transportation", and "RFID in automobiles". The full text was reviewed for all articles that were retrieved and those that did not specifically relate to RFID in transportation were eliminated.

RFID tags have been used for transportation toll systems since the early 1970s (Jones, 2008). Transponder, or tag, based radio frequency systems have been utilized for weigh-in motion and other enforcement actions over the last few decades with systems such as Pre-Pass and North American Preclearance and Safety System (NorPass). The concept of using one RFID based system that can be integrated with RFID toll systems, other transponder based systems, and additional state systems that utilize common information is the foundation for this research. It is envisioned that such a system can be created by having standardized (ISO) RFID tags with the facilities both underground and above ground to be read. Existing readers, that interrogate other transponders, could also read the common information due to the systems' ISO standardization. Multiple aspects of this type of system must be tested for it to be successful. The physical capability of the system is described in this study.

Enforcement operations have a critical need to obtain a more efficient means of capturing data for inspection purposes in comparison to manual "screening" approaches used for enforcement of safety and registration guidelines (Transportation Research Board, 2008). Approaches such as random screening do not allow for sufficient attention to be placed upon those carriers and vehicles most likely to be in violation of the law. These random screenings can be an inefficient use of enforcement resources and can be improved with modern data collection technologies. In order to utilize automated technologies for more effective roadside enforcement, pertinent information must be accessible and collected in a reliable way. In this paper we introduce a means for accomplishing these goals by investigating RFID as a possibility for facilities underground up to 24 inches to be identifiable in ROW project automatically (Mid-America Transportation Center, 2008). One of the greatest challenges for the transportation industry is to investigate and test the feasibility of emerging technologies such as RFID. Another challenge is to identify the advantages of one RFID system over others.

This study utilized multiple attribute decision making analysis to do most suitable decision whether the RFID systems were good choice to be implemented and which RFID system should be the best, considering the reliability of different systems. Reliability is defined as the ability of product or a system to perform consistently.

2.2 Analytic Hierarchy Process (AHP)

Analytic Hierarchy Process (AHP), since its development, has been a tool at the hands of decision makers and researchers; and it is one of the most widely used multiple criteria decision-making tools. Many outstanding works have been published based on AHP: they include applications of AHP in different fields such as planning, selecting a best alternative, resource allocation, resolving conflict, optimization, and numerical extensions of AHP (Vargas, 1990; Zahedi, 1986). Bibliographic review of the multiple criteria decision-making tools carried out by Steuer (Steuer, 2003) is also important.

AHP (Saaty, 1980) is a multiple criteria decision – making tool. This is an Eigen value approach to the pair – wise comparisons. It also provides a methodology to calibrate the numeric scale for the measurement of quantitative as well qualitative performances. The scale ranges from 1/9 for ‘least valued than’, to 1 for ‘equal’, and to 9 for ‘absolutely more important than’ covering the entire spectrum of the comparison.

Users of the AHP first decompose their decision problem into a hierarchy of more easily comprehended sub-problems, each of which can be analyzed independently. The elements of the hierarchy can relate to any aspect of the decision problem – tangible or intangible, carefully measured or roughly estimated, well- or poorly-understood – anything at all that applies to the decision at hand.

Once the hierarchy is built, the decision makers systematically evaluate its various elements by comparing them to one another two at a time. In making the comparisons, the decision makers can use concrete data about the elements, or they can use their judgments about the elements' relative meaning and importance. It is the essence of the AHP that human judgments, and not just the underlying information, can be used in performing the evaluations (Saaty, 2008).

The AHP converts these evaluations to numerical values that can be processed and compared over the entire range of the problem. A numerical weight or priority is derived for each element of the hierarchy, allowing diverse and often incommensurable elements to be compared to one another in a rational and consistent way. This capability distinguishes the AHP from other decision making techniques.

In the final step of the process, numerical priorities are calculated for each of the decision alternatives. These numbers represent the alternatives' relative ability to achieve the decision goal, so they allow a straightforward consideration of the various courses of action.

The applications of AHP can be classified into three groups, namely: (1) applications based on a theme, (2) specific applications, and (3) application combined with some other methodology (Vaidya, 2006). Themes in the first group are selection, evaluation, benefit-cost analysis, allocations, planning and development, priority and ranking, and decision making. Second group consists of the specific applications in forecasting, and medicine and related fields. AHP applied with Quality Function Deployment (QFD) is covered in the third group.

The specialty of AHP is its flexibility to be integrated with different techniques such as Linear Programming, Quality Function Deployment, and Fuzzy Logic. This enables the user to extract benefits from all the combined methods, and hence, achieve the desired goal in a better way.

2.3 Combination Application of AHP and QFD

The success of the project lies in understanding the customer preferences and tastes and anticipating the changes required in existing or new products being offered. Soota's study (Soota, Singh, and Mishra, 2008) uses a heuristic approach to formulate the problem of product development using a combination of analytical hierarchy process (AHP) with quality function deployment (QFD) to evaluate the most satisfying design for customer. A case study for selection of a bike has been presented here to illustrate the proposed approach. The contributions of the study are (a) structuring of the decision problem for assessment of impact of decisions after identification of customer attributes and preferences; (b) assessing strategies to synthesize qualitative and quantitative factors in decision-making, keeping checks on consistency; (c) using the additive synthesis of priorities to accommodate a variety of interactions and transform multidimensional measurements to one-dimensional ratio scale; and (d) assessing the impact of the engineering characteristics weights on the priority of the criteria and overall project (v) validation of the model using a case study.

Also, in order to make the game of soccer more attractive for the soccer enthusiasts, Partovi and Corredoira (Partovi, and Corredoira, 2002) used quality function deployment techniques with AHP. The market segments, and the sports enthusiast's interests, soccer activities and the rules of the games are the rows and columns in the QFD. AHP is used to determine the intensity of the relationship between the rows and the columns of the matrix. Analytic Network Process (ANP) is also used to determine the intensity of the synergy effects among the column variables. A forecasting technique is also used to suggest the rule change specifications.

In order to prioritize the team membership based on the customer's requirements and/or products characteristics, Zakarian and Kusiak (Zakarian, and Kusiak, 1999) used AHP and QFD. The QFD is used to organize the different factors in the team, whereas, the information of each team member is determined by the AHP approach. The model is tested on the selection of the teams in concurrent engineering applications. Two basic matrices are planned together. First uses the co-relation of customer requirements and engineering characteristics. The second uses the characteristics and the team members. The team selection is done by the use of AHP.

In order to improve the industrial engineering quality at an educational institute, Kokasl and Egitman (Koksal, and Egitman, 1998) used QFD and AHP.

Requirements from the different groups associated with Industrial Engineering (IE) education were collected with the aid of surveys and interviews. The groups of people associated with IE education were students, faculty members and the future employees of the students. The requirements from them were prioritized by the use of AHP.

Table 1 Studies in Combination of AHP and QFD

Sr. No.	Year	Author/s	Application areas	Tools used
1	1994	Armacost R.L. et al.	Social	AHP, QFD
2	1996	Bryson N.	Personal	AHP, QFD
3	1998	Koksal G., Egitman A.	Education	AHP, QFD
4	1999	Ho E.S.S.A. et al.	Personal	AHP, QFD
5	1999	Zakarian A., Kusiak A.	Personal	AHP, QFD
6	2002	Partovi F.Y., Corredoira R.A.	Sports	AHP, ANP, QFD
7	2003	Myint S.	Engineering	AHP, QFD
8	2008	Soota T., Singh H., Mishra R.	Social	AHP, QFD

2.4 Quality Function Deployment (QFD)

Quality function deployment (QFD) is "an overall concept that provides a means of translating customer requirements into the appropriate technical requirements for each stage of product development and production (i.e., marketing strategies, planning, product design and engineering, prototype evaluation, production process development, production, and sales)" (Sullivan, 1986). QFD is a "method to transform user demands into design quality, to deploy the functions forming quality, and to deploy methods for achieving the design quality into subsystems and component parts, and ultimately to specific elements of the manufacturing process." (Akao), as described by Dr. Yoji Akao, who originally developed QFD in Japan in 1966.

QFD was originally proposed, through collecting and analyzing the voice of the customers, to develop products with higher quality to meet or surpass customer's needs. Thus, the primary functions of QFD are product development, quality management, and customer needs analysis. Later, QFD's functions were expanded to wider fields such as product design, planning, engineering, decision-making, management, teamwork, timing, and costing (Chan and Wu, 2002). QFD determines product design specifications (hows) based on customer needs (whats) and competitive analysis (whys), which represents a customer-driven and market oriented process for decision-making.

QFD is designed to help planners focus on characteristics of a new or existing product or service from the viewpoints of market segments, company, or technology development needs. The technique yields graphs and matrices. It is applied in a wide variety of services, consumer products, military needs, and emerging technology products. The technique is also used to identify and document competitive marketing strategies and tactics. It is considered a key practice of Design for Six Sigma. It is also implicated in the new ISO 9000:2000 standard which focuses on customer satisfaction.

Results of QFD have been applied in Japan and elsewhere into deploying the high – impact controllable factors in strategic planning and strategic management. In addition, the same technique can extend the method into the constituent product subsystems, configuration items, assemblies, and parts. From these detail level components, fabrication and assembly process QFD charts can be developed to support statistical process control techniques. The data in QFD has potential to be utilized into the AHP.

2.5 The Economic Analysis

Except the multi-attribute decision methodologies described above (the AHP), another type of decision analysis should be utilized to compare with the multi-attribute decision analysis. The economic analysis is selected as the contrast.

The traditional method to analyze the economical benefits of an investment project is using Discounted Cash Flow (DCF) to calculate Net Present Value (NPV) and to analyze the feasibility of a project. Though it is the most conventional method for economical analysis and decision making, there are some limitations that may contribute to unsuitable decisions or results. The natural disadvantages of DCF often cause investors to estimate the value of a project too low or make a wrong decision. This is especially true for a project with flexibility and a growth strategy that involves potential investment opportunities. To consider these uncertainties, an alternative methodology to DCF must be used.

One alternative, real options, was developed by Stewart Myers (MIT) in 1977. The underlying security of the real option is a tangible good, not stock or futures. A real option is the right, but not the obligation, to take an action at a predetermined cost for a predetermined period of time. Real Options Analysis (ROA) offers a way to accommodate for time progression and previously unknown factors. Unlike the more traditional techniques, real options analysis explicitly accounts for future flexibility. Compared to traditional techniques for evaluating investment decisions in organizations such as DCF and NPV, the real options approach recognizes the value of managerial flexibility. Such flexibility is important in situations dealing with structuring and timing investment decisions, especially in the face of uncertain conditions, varying levels of risks at different stages of an investment project, and irreversible investments (Goswami, Teo and Chan, 2008).

RFID projects contain numeric uncertainties, including trading-partner RFID adoption, tag costs, technology capabilities, and evolving standards. In this way, RFID projects meet the requirements for using ROA. Organization decision makers may intuitively realize the strategic potential from investing in RFID even if initial returns look unfavorable. They are likely to hesitate before investing due to the current uncertainty pertaining to the technology and the way it is going to evolve over time, thus causing man gets to wait for more information before investing in the technology. Further, they might also realize that while investing in RFID is somewhat irreversible, they have the flexibility of structuring the investment project in small incremental steps (Goswami, Teo and Chan, 2008).

There are many different real options that have been identified in prior research. One is the growth option, which considers the future growth opportunities that can be realized from an initial investment. Another is the deferral option, which is the option to wait and delay an investment until more information arrives. The third one is the learning option, which is the option to learn and gather information and reduce uncertainty through an initial investment. The fourth one is the staging option, which is the choice of breaking up an investment into incremental conditional steps where each step is carried out after the successful completion of prior steps. The fifth one is the option to change scale, which has the flexibility to respond by altering the capacity. The sixth one is the option to switch, which has the ability to put the initial investment into an application different from what it was initially intended for. The seventh one is the option to abandon, which is the option to discontinue a project (Brach, 2003; Kogut and Kulatilaka, 1994; Fichman et al., 2005; Tiwana et al., 2006; Tiwana et al., 2007).

In the DOT project associated with this thesis, based on the initial cost model, a compound real option model (Wei, L. and Yuan, L., 2004) was used to evaluate the different types of RFID systems identified for this project. For research and development, the investment was known as D at the beginning, X for testing the property of the system in a real environment at the end of year t_1, and M for comprehensive implementation at the end of year t_2. Depending on these investments and revenue, the initial value of the project can be estimated for different types of RFID systems, marked as V_0.

Chapter 3 Rationale

The research objective of this thesis is to compare the effectiveness of making multi-attribute decisions due to the uncertainty of group decisions. A method is demonstrated that allows for customer based quality considerations to be considered given a set of constraints. In this research, a model is introduced that combines the Quality Function Deployment (QFD)/ House of Quality (HOQ) matrix with the Analytic Hierarchy Process (AHP) in order to create a tool that allows for multi attributes decisions. Two accepted economic decision approaches are utilized to evaluate the model. Further, data sets from a DOT project case study to demonstrate the usage of the model are utilized. Three main research questions were investigated in order to achieve our research objective.

1) How can the QFD results be integrated into the AHP analysis for making more effective decisions?

2) How does the quality based AHP model compare to the model with uncertain conditions?

3) How does the quality based AHP model compare to other accepted models given a DOT project scenario and data set?

Chapter 4 Methodology

In this chapter, the main methodology utilized in the approach is introduced. There is rationale of the basic methodology utilized, data collection, analysis plan, and the procedure of the approach included in this chapter. The basic methodologies include the Quality Function Deployment (QFD), the Analytic Hierarchy Process (AHP), and two economic decision-making analyses (Decision Tree and Real Option Analysis). These decision making tools are applied to the selection of an RFID system in a DOT Right of Way management of inventory case study.

4.1 Procedure of the Approach

The Quality Function Deployment (QFD) was utilized first. At the same time, the Performance Evaluation (PE) of the six RFID systems was done. Then the basic Analytic Hierarchy Process (AHP) was used based on the QFD and the PE data. The Benefits from the project were calculated utilizing Decision Tree (DT) and Real Option Analysis (ROA), and the AHP was utilized in combining the benefits obtained from the previous steps. The results by the DT and ROA were compared with the results from the AHP analysis.

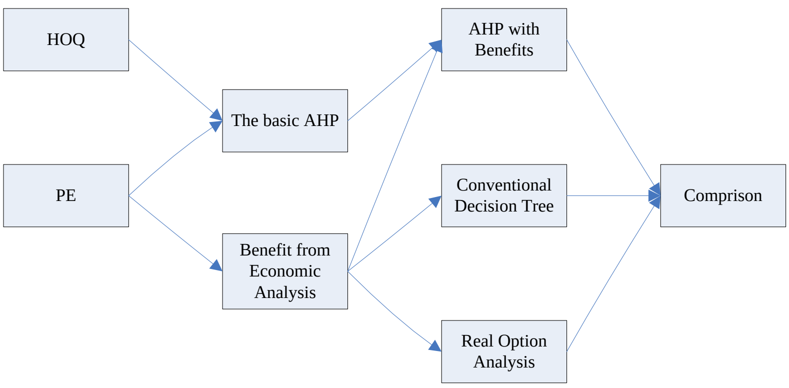

Figure 2 Approach for the research

4.2 Rationale

4.2.1 Quality Function Deployment

A Quality Function Deployment tool (QFD) uses a matrix process to collect topics that are essential to the planning process. The House of Quality Matrix is a highly recognized and widely used form of this method. This method was used for translating customer or stakeholder requirements into functional design.

There are four major characteristics of QFD as a quality system. First, QFD is a quality system that integrates elements of system thinking, e.g. viewing the development process as a system, and the psychology or being able to conceptualize customer concerns, what value is being determined, and how customers or end users become interested, choose, and are finally satisfied. Second, QFD is a quality method of good knowledge or epistemology. This addresses how the needs of the customer are determined, which features are to be incorporated, and what level or degree of performance is to be determined. Thirdly, QFD is a strategy for competiveness. It maximizes positive quality that adds good worth. It brings outspoken and unspoken customer needs or request and translates them into technical functions. A QFD prioritizes concerns and directs the contributor to optimize those features that will bring the greatest competitive advantage. Finally, Quality Function Deployment is the only comprehensive quality system targeted specifically at satisfying the customer through the development and business process as from beginning to end.

The steps to developing a QFD are as follows:

1. Develop a list of customer requirement,
2. Develop a listing of technical design elements along the roof of the house,
3. Demonstrate the relationships between the customer requirements and technical design elements,
4. Identify the correlations between design elements in the roof of the house,
5. Perform a competitive assessment of the customer requirement,
6. Prioritize customer requirement,
7. Prioritize technical requirement, and
8. Final evaluation.

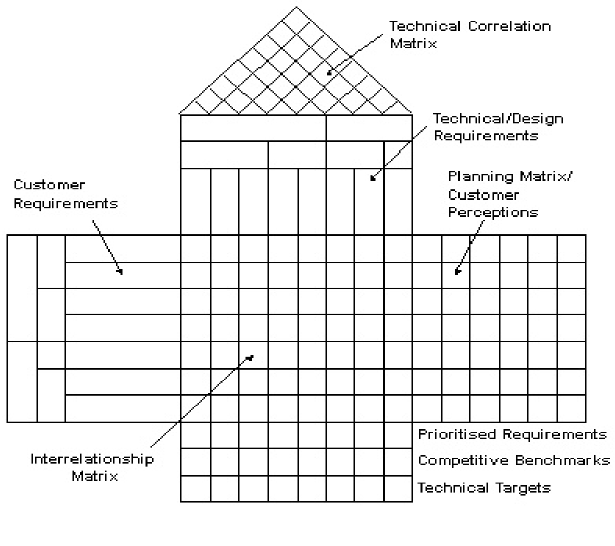

Figure 3 General house of quality structure

Standard structure for the House of Quality (HOQ) is shown in Figure 3 above. The tool takes customer preferences and demands and then translates them into technical requirements that can be quantified, measured, and analyzed. These results can then be used to determine the focus of experiments and research.

The HOQ can be divided into eight different sections. These sections (or rooms) are sometimes referred to as the “What”, Importance and Customer Competitive Assessment, “How”, Relationship, Absolute and Relative Score, Correlation Matrix, Technical Competitive Assessment, and Target Value “rooms” (Squires, 2009). The “What” room is the section that houses customer requirements as seen on Figure 3. The Importance Ratings and Customer Competitive Assessment “room” contains information grouped for analysis, and is located on the right area of Figure 3 labeled as Planning Matrix/Customer Perceptions. The “How” room is the area that lists the measurements that will be used for each “What” and is labeled Technical/Design Requirements at the top of Figure 3. The “Relationship Matrix” room or Interrelationship Matrix area of the HOQ explores all of the interactions between the various “whats” and “hows”. The Absolute and Relative Score rooms also known as the Prioritized Requirements area is at the bottom of the HOQ, and is where the total scores for each “how” are evaluated based on several factors. The next area known as the Correlation Matrix is where the relationships between the various “hows” or technical requirements are evaluated. Some of these may benefit each other, or stand in direct contradiction and knowledge of these interactions aids the design process in optimizing the various requirements. The Technical Competitive Assessment room is also known as the Competitive Benchmarks near the bottom of the HOQ, which evaluates how the product compares to similar competing products. The final area is the Target Values or the Technical Targets area at the bottom of the HOQ, which lists the recommended specifications for the given product. These specifications have been systematically determined, displaying the customer concerns and also competitively offering any technical trade-off suggested due to design or manufacturing constraints (Squires, 2009).

For the project of the thesis, stakeholder requirements were gathered in a kick off session. The stakeholder requirements for the Department of Transportation in Right of Way Project were focused around using RFID readers for data collection and facilities management underground.

After collecting the stakeholder requirements, a HOQ analysis was performed for the stakeholder in the project. From each analysis, a ranking of technical requirements was developed. After all HOQ studies had been completed the rankings were tallied and an overall composite technical requirement ranking was assigned. As the results, the relative and absolute weights for technical requirements was evaluated to determine what decisions need to be made to improve the design based on customer input.

4.2.2 Analytic Hierarchy Process

The analytic hierarchy process (AHP) was developed and documented primarily by Thomas Saaty (Saaty, 1980; Saaty, 1982). The AHP theory has be applied in numerous fields, such as transportation planning, portfolio selection, corporate planning, marketing, and others.

The strength of the AHP method lies in its ability to structure a complex technological, economic, and socio-political problems with multiperson, multiattribute, and multiperiod hierarchically (Saaty and Vargas, 1991). Pairwise comparisons of the elements (usually, alternatives and attributes) can be established using a scale indicating the strength with which one element dominates another with respect to a higher-level element. This scaling process can then be translated into priority weights (scores) for comparison of alternatives (Canada, 1989).

The mathematical foundations are simple, and its purpose is to make a contribution towards unity in modeling real-world problems. The major assumptions in this methodology are the methods to pursue knowledge, to predict, and to control the world are relative, and the goal to use the methodology is itself relative (Saaty, 1991). Saaty uses the term “element” to apply to the overall objective, attribute, subattributes, sub-subattributes, and so on; and alternatives of a problem as follows:

> *The top level, called the focus, consists of only one element – the broad, overall objective. Subsequent levels may each have several elements, although their number is very small – between 5 and 9.*

Because the elements in one level are to be compared with one another against a criterion in the next higher level, the elements in each level must be of the same order of magnitude (Saaty, 1982).

As a typical four-level hierarchy applied to a car choosing problem, the focus is at the top level and the alternatives are at the lowest level. If any of the subattributes were further divided into sub-subattributes, those sub-subattributes would have constituted a new level.

The general approach of the AHP is to decompose the problem and to make pairwise comparisons of all elements (attributes, alternatives, etc.) on a given level with respect to the related elements in the level just above. The degree of preference or intensity of the decision maker in the choice for each pairwise comparison is quantified on a scale of 1 to 9, and these quantities are placed in a matrix of comparisons. The suggested numbers to express degrees of preference between the two elements a_i and a_j are seen in Table 2.

Table 2 Trans-quantitative Scores

a_{ij}	1	2	3	4	5	6	7	8	9
the importance of a_i:a_j	fair		weakly strong		strong		obviously strong		absolutely strong

Even numbers (2, 4, 6, and 8) can be used to represent compromises among the preferences above.

A matrix of comparisons for all elements is next constructed with preference numbers obtained as above. For inverse comparisons such as a_j to a_i, the reciprocal of the preference number for a_i to a_j (above) is used.

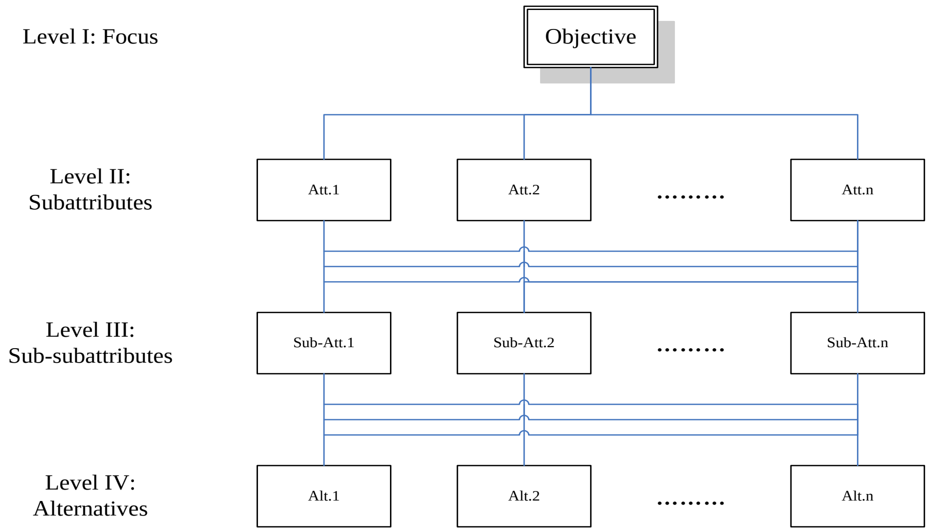

Figure 4 Sample analytic hierarchy diagram

The basic solution process can be concluded as follows (Vaidya and Kumar, 2004):

1. State the objective;

2. Identify the attributes and alternatives, which are related with the objective of the problem;

3. Structure the attributes and alternatives in a hierarchy of different levels constituting subattributes, sub-subattributes and alternatives, a sample with four levels in the AHP shown in Figure 4;

4. Compare the importance of each element in the same level to the one higher level and calibrate them on the numerical scale: there will be n(n-1)/2 comparisons, where n is the number of elements with the considerations that diagonal elements are equal and the other elements will simply be the reciprocals of the earlier comparisons;

5. Calculate out the weight modulus of every index;

6. Calculate the maximum Eigen value of comparison results, consistency index CI, consistency ratio CR for each attributes/alternative; and

7. If the maximum Eigen value, CI, and CR are satisfied then decision is taken based on the weight modulus; else the procedure should be repeated until these values lie in a desired range.

In research of this thesis, the objective is to use the data from QFD into AHP. The top level of AHP as the objective is the best RFID system implemented in this project. Attributes are customers' requirements and technical requirements. Level II as the subattribute is the customer requirements, while Level III as the sub-subattribute is the technical requirements. Level IV (the lowest level) is six different RFID systems which have potential to be implemented in this project as the alternatives (Zakarian and Kusiak, 1999). Based on the final weights of the lowest level, the most suitable alternative can be selected and suggested as the best investment in the multiattribute decision analysis.

4.2.3 Benefit Evaluation of the RFID Systems Implementation

In this project, the benefits of implementing different RFID systems are the most important attributes in the AHP, which can influence the decision obviously.

The project can be divided into three stages, which are the development phase, trial phase, and implementation phase shown in Figure 5. This project can bring savings to the DOT, although there are costs and risks in each phase.

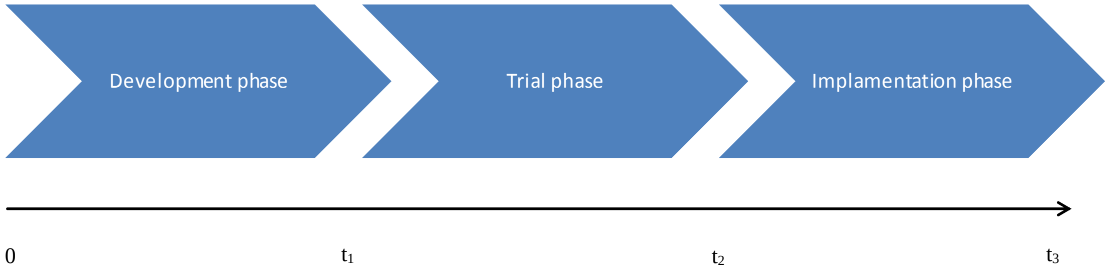

Figure 5 Stages for analysis

The traditional method to analyze the risk of an investment project is using Decision Tree (DT) probabilities with Net Present Value (NPV) and to analyze the feasibility of a project.

Using the conventional decision tree analysis the expected NPV of this three stages project for different RFID systems can be determined. This value can then be used to determine the system to be implemented. A sample of the decision tree is shown in Figure 6.

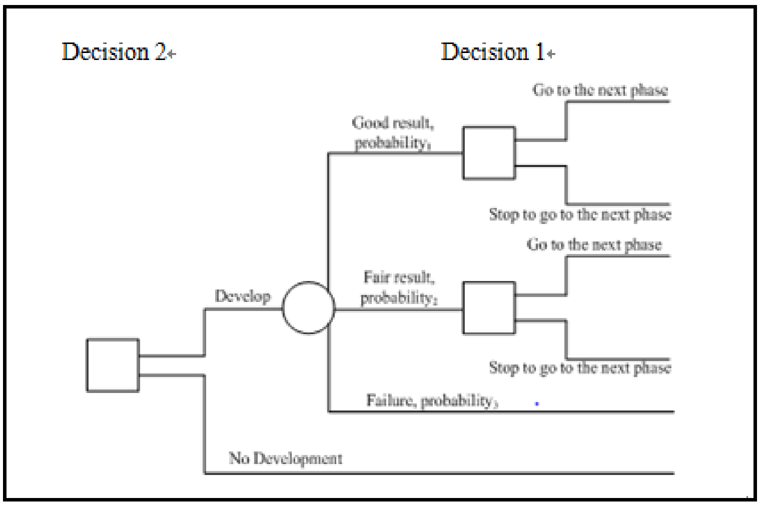

Figure 6 Decision tree as sample

To consider these uncertainties, Real Option Analysis (ROA) is used as an alternative methodology to DCF. ROA offers a way to accommodate for time progression and previously unknown factors. Unlike the more traditional techniques, real options analysis explicitly accounts for future flexibility. Such flexibility is important in situations dealing with structuring and timing investment decisions, especially in the face of uncertain conditions, varying levels of risks at different stages of an investment project, and irreversible investments (Goswami, Teo and Chan, 2008).

There are many different real option methods that have been identified in prior research (Brach, 2003; Kogut and Kulatilaka, 1994; Fichman et al., 2005; Tiwana et al., 2006; Tiwana et al., 2007).

Obviously, the compound real option model can be utilized in this project (Wei, L. and Yuan, L., 2004) to evaluate the different types of RFID systems. For research and development, the investment was known as D at the beginning, X for testing the property of the system in a real environment at the end of year t_1, and M for comprehensive implementation at the end of year t_2. Depending on these investments and revenue, the initial value of the project can be estimated for different types of RFID systems, marked as V.

4.3 Data Collection

In the process to do this project, seven meetings were held to get information from the stakeholder – the Department of Transportation. Based on brainstorm, some questions were created before the meeting and asked to the stakeholder in the meeting. After the meeting, the information collected was concluded together and extracted the useful information to create the House of Quality by the participants in the meeting.

The costs of different RFID systems were from the retailers who supplied the systems. How much it should be invested was determined by the discussion of the stakeholders and the experts together, and then the investment (D, X, M) in different stages of the project can be decided. The saving (V) from implementation of RFID systems against current systems can be estimated by the stakeholders.

In this project, many experiments testing the performance of different RFID systems with different levels of factors were done. The experts who did the experiments and analyzed the results from the experiments evaluated the performances of different RFID systems under different conditions. These conditions were type of the communication media from tag to antenna, materials tag adhered, buried tag distance from surface, vertical antenna distance from ground, and horizontal antenna distance from tag. The scores (PS) given were from 1 to 10 that 10 means the best performance and 1 means the poorest performance, while 0 means the tag cannot be read by the reader.

As shown above, the customer requirements were on Level II in the AHP, and each customer requirement was one subattribute to Level I. The comparison was between the absolute weights (AW_i) of two customers' requirements. The technical requirements were on Level III in the AHP, and all or part of technical requirements was subattributes to one attribute in Level II and sub-subattributes to Level I. The comparison was between the relationship scores (*CT*) of two technical requirements for each customer requirement respectively. The comparison of different alternatives was based on the performance and benefit received of each RFID system.

4.4 Analysis Plan

4.4.1 Quality Function Deployment Analysis

Following the steps shown in Section 4.2.1, the major customer requirements related to a particular aspect of the process were developed first. And then the technical requirements were related to customer requirements. A diagram is used to demonstrate the relationships between the customer requirements and the technical requirements shown in Figure 9 as an example. The scores (CT_{ij}), where i is index for customer requirements, and j index for technical requirements, were assigned relating to the symbols, i.e., 1, 3 and 9, where 9 means strongly associated, 3 is somewhat associated and 1 is weakly associated. For example, $CT_{11} = 9$, where the first 1 means the 1^{st} customer requirements – Timely phone service, and the second 1 means the 1^{st} technical requirements – Type of phone. Their relationship score is 9 shown in Figure 7.

The correlations are shown above the technical requirements using symbols to show whether different design elements were positively or negatively correlated. The competitive assessment shows how the product compares with those of the key competitors. There were two assessments in one house of quality, one for customer requirements and another for technical requirements.

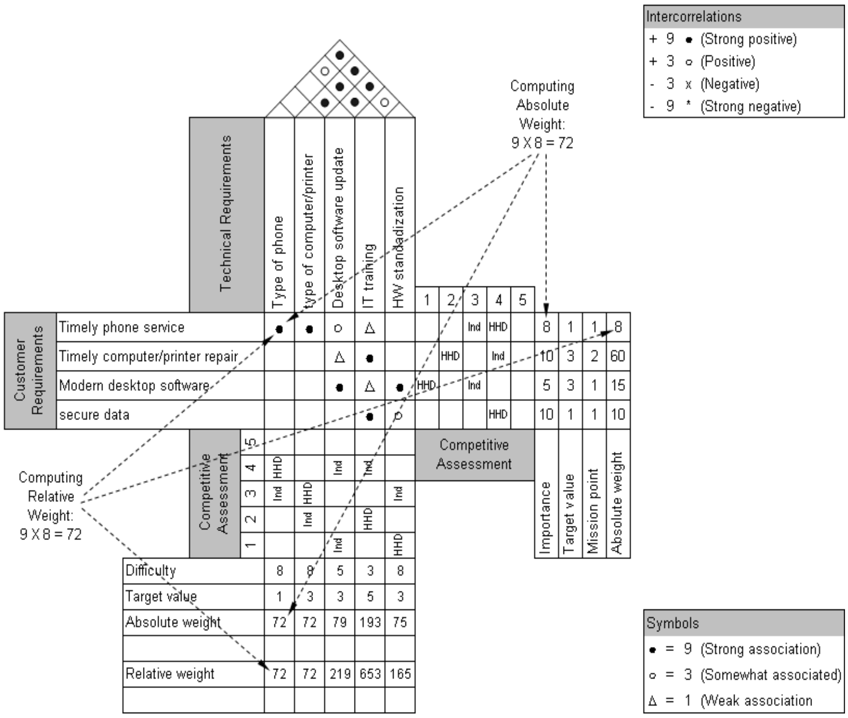

Figure 7 Example of the qfd diagram

Priorities of customer requirements include importance to customer (*I*), target value (*TV*), mission point (*MP*), and absolute weight (AW_i) on the far right side. Importance is on a 10-point scale, with 10 being most important. Target values are set on a 5-point scale where 1 is no change, 3 is improving the product, and 5 is making the product better than the competition. The sales point is established on a scale of 1 or 2, with 2 meaning high-sales effect and 1 being low effect.

$$AW_i = I_i \cdot TV_i \cdot MP_i \qquad \text{(Equation 1)}$$

where

AW_i = the absolute weight of the ith customer requirement;

I_i = the importance of the ith customer requirement;

TV_i = the target value of the i^{th} customer requirement;

MP_i = the mission point of the i^{th} customer requirement; and

i = index for customer requirements.

The absolute weight is found by multiplying importance, target values and sales point. It has 100 as the highest score and 1 as the lowest score.

Priorities of technical requirements include difficulty, target value, absolute weight (AW_j), and relative weight (RW_j). The degree of difficulty is on a 10-point scale, with 10 being most difficult. The target value is defined the same way the target values for the customer requirements. The value for absolute weight is the sum of the products of relationships between customer and technical requirements and the importance to the customer columns. The value for relative weight is the product of the column of relationships between customer and technical requirements and customer requirements absolute weights.

As shown above in Figure 7, the absolute weight of the j^{th} technical requirement is

$$AW_j = \sum_{i=1}^{n} CT_{ij} \cdot I_i, \qquad \text{(Equation 2)}$$

and the absolute factor of the j^{th} technical requirement is

$$AF_j = \mathrm{AW_j} / \sum_{j=1}^{m} AW_j. \qquad \text{(Equation 3)}$$

The relative weight of the j^{th} technical requirement is

$$RW_j = \sum_{i=1}^{n} CT_{ij} \cdot AW_i, \qquad \text{(Equation 4)}$$

and the relative factor of the j^{th} technical requirement is

$$RF_j = \mathrm{RW_j} / \sum_{j=1}^{m} RW_j. \qquad \text{(Equation 5)}$$

where

AW_j = the absolute weight of the j^{th} technical requirement;

CT_{ij} = the relationship scores between the i^{th} customer requirement and the j^{th} technical requirement;

I_i = the importance of the i^{th} customer requirement;

AF_j = the absolute factor of the j^{th} technical requirement;

RW_j = the relative weight of the j^{th} technical requirement;

AW_i = the absolute weight of the i^{th} customer requirement;

RF_j = the relative factor of the j^{th} technical requirement;

i = index for customer requirements;

j = index for technical requirements;

n = the total number of customer requirements; and

m = the total number of technical requirements.

4.4.2 Benefit Evaluation Analysis

The Conventional Decision Tree Model

The conventional decision tree for this project is developed. The expected Net Present Value (*NPV*) of implementing RFID systems is

$$NPV = \frac{F}{(1+r)^n} - \text{Inv.} \qquad \text{(Equation 6)}$$

where

NPV = the Net Present Value;

F = the future value in the end of the n$^{\text{th}}$ year;

r = the effective riskless interest rate annually;

Inv. = Investment at beginning of the period.

Two decisions were made in this decision tree from right to left. The square symbol indicates where a decision needs to be made. To make Decision 1, the net present value in the Trial Phase should be compared with no action. In order, to make Decision 2, the net present value in the Development Phase should be compared with no investment. And then the NPV of the project utilizing the correlated RFID system can be found.

The expected net present values in Decision 1 are

$$E\left[NPV_{good}\right] = V_{success} \times B_1 + V_{failure} \times B_2 - X \qquad \text{(Equation 7)}$$

$$E\left[NPV_{fair}\right] = V_{success} \times C_1 + V_{failure} \times C_2 - X \qquad \text{(Equation 8)}$$

based on different results (good or fair results) respectively in Development Phase, where

$V_{success}$ = the present value of the savings with successful results in Trial Phase;

$V_{failure}$ = the present value of the savings with failure in Trial Phase;

X = the present value of the investment in Trial Phase;

M = the present value of the investment in Implementation Phase;

$E[NPV_{good}]$ = the expected net present value in Decision1 based on good results in Development Phase;

B_1 = the probability of success in Trial Phase based on good results in Development Phase;

B_2 = the probability of failure in Trial Phase based on good results in Development Phase;

$E[NPV_{fair}]$ = the expected net present value in Decision1 based on fair results in Development Phase;

C_1 = the probability of success in Trial Phase based on fair results in Development Phase; and

C_2 = the probability of failure in Trial Phase based on fair results in Development Phase.

The expected net present value in Decision 2 is

$$E[NPV] = E[NPV_{success}] \times A_1 + E\left[NPV_{failure}\right] \times A_2 + V'_{failure} \times A_3 - D$$

(Equation 9)

where

$E[NPV]$ = the expected net present value of the project;

$E[NPV_{good}]$ = the expected net present value in Decision1 based on good results in Development Phase;

$E[NPV_{fair}]$ = the expected net present value in Decision1 based on fair results in Development Phase;

$V'_{failure}$ = the present value of the savings with failure in Development Phase;

D = the present value of the investment in Development Phase;

A_1 = the probability of good results in Development Phase;

A_2 = the probability of fair results in Development Phase; and

A_3 = the probability of failure in Development Phase.

The Compound Real Option Model

Due to the selection of a compound real option model, Binomial Lattice Model can be utilized to solve the real option problem (Cox, 1979). This can be a general solution to most problems, and it is applied to calculate the early decision points.

Figure 8 illustrates the procedures for deciding the early exercise in node by a binomial lattice approach. The initial stock price, V_0, will move to one of the two values, V_0u and V_0d, during the first time interval. The two values also will move to two possible directions, “up” and “down”, during the next time interval, and so on.

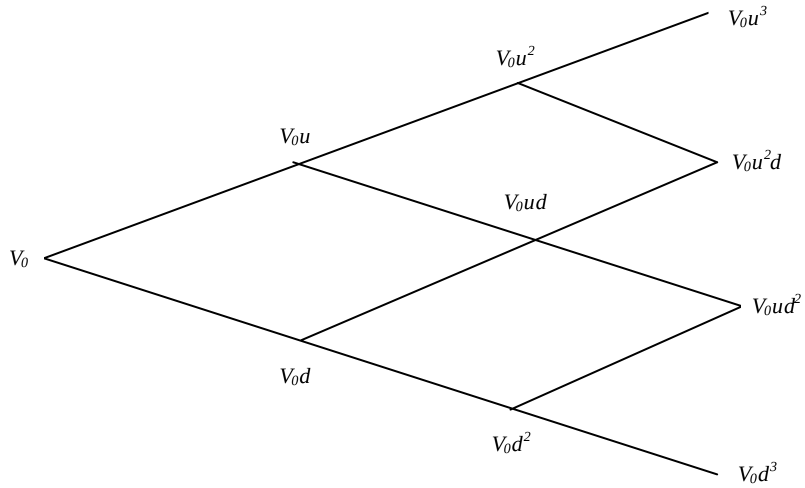

Figure 8 Binominal tree approach for early exercise decision

The parameter u represents an “up” movement and d a “down” movement during a time interval Δt. Usually, u and d are given by the next equations based on lognormal distribution, and σ is the volatility of the logarithmic rate of return of V.

$$u = e^{\sigma\sqrt{\Delta t}} \quad \text{(Equation 10)}$$

$$d = e^{-\sigma\sqrt{\Delta t}} \quad \text{(Equation 11)}$$

The other parameters in the lattice are p from Equation 12, which represents the probability that the stock price takes an "up" movement; *1-p*, which is the probability that the stock price moves "down"; r, the risk-free interest of the model, and "*M*" represents the strike price of the options (Han and Park, 2008).

$$p = \frac{R-d}{u-d} = \frac{(1+r)-d}{u-d} \qquad \text{(Equation 12)}$$

First, it needs to be determined whether the option should be exercised at the maturity time t by Equation 13. The value of a call option C_t at time t can be shown as

$$C_t = \max(V_t - M, 0) \qquad \text{(Equation 13)}$$

If the value of the call option is 0, it means this option is not valuable to be exercised in this state; if the value of the call option is $V_t - M$, it means this option should be exercised in this state. The value of the option at the previous node can be expressed as

$$C_{t-1} = \frac{pC_{tu} + (1-p)C_{td}}{1+r} \qquad \text{(Equation 14)}$$

By using Equation 14, the present value of the call option C_0 can be obtained.

In this case, a compound option, there are two maturity times and two strike prices. When iterating to get the value of the option at time t_1, one still has the right to decide whether this investment should be made, and it is the strike price of this stage. So at time t_1, the following decision should be made.

$$C_{t_1} = \max\left(\frac{1}{1+r}(qC_{(t_1+1)u} + (1-q)C_{(t_1+1)d}) - X, 0\right) \qquad \text{(Equation 15)}$$

If the value of C_{t_1} is 0, it means this compound option is not valuable to be exercised in this state; if the value of C_{t_1} is not 0, it means this option is valuable to be exercised in this state at time t_1. After the decision here made, Equation 14 should be utilized to obtain the present values of the compound option to evaluate the RFID systems implementation in ROW. They can be utilized to the AHP analysis.

4.4.3 Analytic Hierarchy Process Analysis

If a problem is stated, there must be several factors influencing it. Hierarchical structure can be built based on these factors, and the direct factors as subattributes for the objective are supposed to be in the one lower level than the objective. The factors as sub-subattributes which may influence the objective through influencing the direct factors should be in the one lower level than the direct factors. The pairwise comparison of the attributes in the same level can be justified. The weight modulus of these was calculated, and decision was made according to the calculation.

Assume $f_1, f_2, \ldots, f_n$ are the factors, and $w_1, w_2, \ldots, w_n$ are weight modulus. The linear equation can be

$$y = w_1 f_1 + w_2 f_2 + \cdots + w_n f_n, where\ w_i \geq 0 \qquad \text{(Equation 16)}$$

$$\sum_{i=1}^{n} w_i = 1 \qquad \text{(Equation 17)}$$

which are the functions to do comprehensive decision.

The results of pairwise comparisons can be put into a matrix $\mathbf{A}_{n\times n}$, and the element in matrix is a_{ij}.

$$A_{n\times n} = \begin{bmatrix} a_{11} & \cdots & a_{1n} \\ \vdots & \ddots & \vdots \\ a_{n1} & \cdots & a_{nn} \end{bmatrix} \qquad \text{(Equation 18)}$$

where

n = the total number of the attributes in the level;

$a_{ij} = a_i/a_j$;

i = index for the rows of the matrix; and

j = index for the columns of the matrix.

To estimate the elements a_{ij} (= a_i:a_j) in the matrix $A_{n\times n}$, one must get a_i and a_j first. Since defined by Saaty the range of a_{ij} is the integer from 1 to 9, the raw scores should be normalized if they are out of the range.

Assume the range of the raw data is [c, d]. The normalized score a_i is

$$a_i = \begin{cases} 9 - \frac{(9-1)\times(d-a_i')}{(d-c)}, & \text{if the attribute i is positively influenced} \\ 9 - \frac{(9-1)\times(a_i'-c)}{(d-c)}, & \text{if the attribute i is negatively influenced} \end{cases} \quad \text{(Equation 19)}$$

where

a_i = the normalized score of attribute i;

a'_i = the raw score of attribute i;

d = the upper limit of the raw scores; and

c = the lower limit of the raw scores.

The vector (**W**) for the weight modulus w_i is

$$W = lim_{n\to\infty} W_k = [w_1 \quad \cdots \quad w_n]^T \quad \text{(Equation 20)}$$

where

$\boldsymbol{W}_k = \frac{\boldsymbol{W}'_k}{\|\boldsymbol{W}'_k\|}$;

$\boldsymbol{W}'_k = \boldsymbol{A}\boldsymbol{W}_{k-1}$;

$\|\boldsymbol{W}_k'\|$ = the sum of the n components of $\boldsymbol{AW}_{k-1}$;

$\boldsymbol{W}_0 = [1/n\ 1/n\ \ldots\ 1/n]^T$;

$k = 1, 2, 3, \ldots$;

n = the total number of the attributes in the level.

W can be calculated only if the sequence of $\{\mathbf{W}_k\}$ is convergent.

If we have $\mathbf{W} = [w_1 \ldots w_n]^T$, the matrix whose entries are w_i/w_j is a consistent matrix which is our consistent estimate of the matrix A. If a_{ij} represents the importance of criterion i over criterion j and a_{jk} represents the importance of criterion j over criterion k, then a_{ik}, the importance of criterion i over criterion k, must equal $a_{ij}a_{jk}$, for the judgments to be consistent. A itself need not be consistent; i.e., A_1 may be preferred to A_2 and A_2 to A_3, but A_3 is preferred to A_1. What one would like is a measure of the error due to inconsistency. A necessary and sufficient condition for A to be consistent is that $\lambda_{max} = n$. $\lambda_{max} \geq n$ always holds. As a measure of deviation from consistency the consistency index (CI) was developed: (Saaty and Vargas, 1991)

$$CI = (\lambda_{max} - n)/(n - 1) \qquad \text{(Equation 21)}$$

where λ_{max} is the maximum characteristic root of the matrix A, and n is the total number of attributes in the level.

Saaty also defined a random index RI shown in Table 3.

Table 3 Random index

n	1	2	3	4	5	6	7	8	9	10	11
RI	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49	1.51

When the ratio $CR=CI/RI<0.1$, it passes the consistency test, otherwise it fails which means it is not powerful enough.

The weighted evaluation for each attributes in the lower level can be obtained by multiplying the matrix of evaluation ratings by the vector of attributes weights in the higher level. Expressed in conventional mathematical notation,

$$g_j = \sum_{i=1}^{n} w_i \cdot g_{ij} \qquad \text{(Equation 22)}$$

where

g_j = the weight modulus evaluated for the attributes j in the lower level;

w_i = the weight modulus evaluated for the attributes i in the higher level;

g_{ij} = the evaluation ratings for the attributes j in the lower level to the attribute i in the higher level; and

n = the total number of attributes in the higher level.

The vector (**G**) for the attributes in the lower level composed by the weight modulus (g_j) is **G** = [g_1 g_2 ... g_m], where m is the total number of attributes in the lower level.

In the multiple cases, the consistency index for the lower level (CI_L) can be obtained from the consistency index for the matrix of the attributes in the lower level to the attribute i in the higher level (CI_{Li}) and the weight modulus of the attribute i in the higher level (w_i).

$$CI_L = \sum_{i=1}^{n} w_i \cdot CI_{Li} \qquad \text{(Equation 23)}$$

where

CI_L = the consistency index for the lower level;

CI_{Li} = the consistency index for the matrix of the attributes in the lower level to the attribute i in the higher level;

w_i = the weight modulus of the attribute i in the higher level;

i = index of the attributes in the higher level; and

n = the total number of attributes in the higher level.

The consistency ratio (CR) of the AHP was the sum of all consistency ratios for every level.

$$CR = \sum_{l=2}^{L} CR_l \qquad \text{(Equation 24)}$$

where

CR = the consistency ratio for the AHP;

CR_l = the consistency ratio for level l except level I since there is only objective in Level I;

l = index for the levels; and

L = the total number of levels in the AHP.

Chapter 5 Results

In this chapter, the specific results and analysis are included. There are the results of the Quality Function Deployment (QFD), the basic Quality based Analytic Hierarchy Process (QAHP), Sensitivity of the basic QAHP and the Quality based Analytic Hierarchy Process (AHP) with uncertainty considerations.

5.1 Quality Function Deployment

Stakeholder requirements were gathered in a kick off session. The stakeholder requirements for the Department of Transportation in Right of Way Project were focused around using RFID readers for data collection and facilities management.

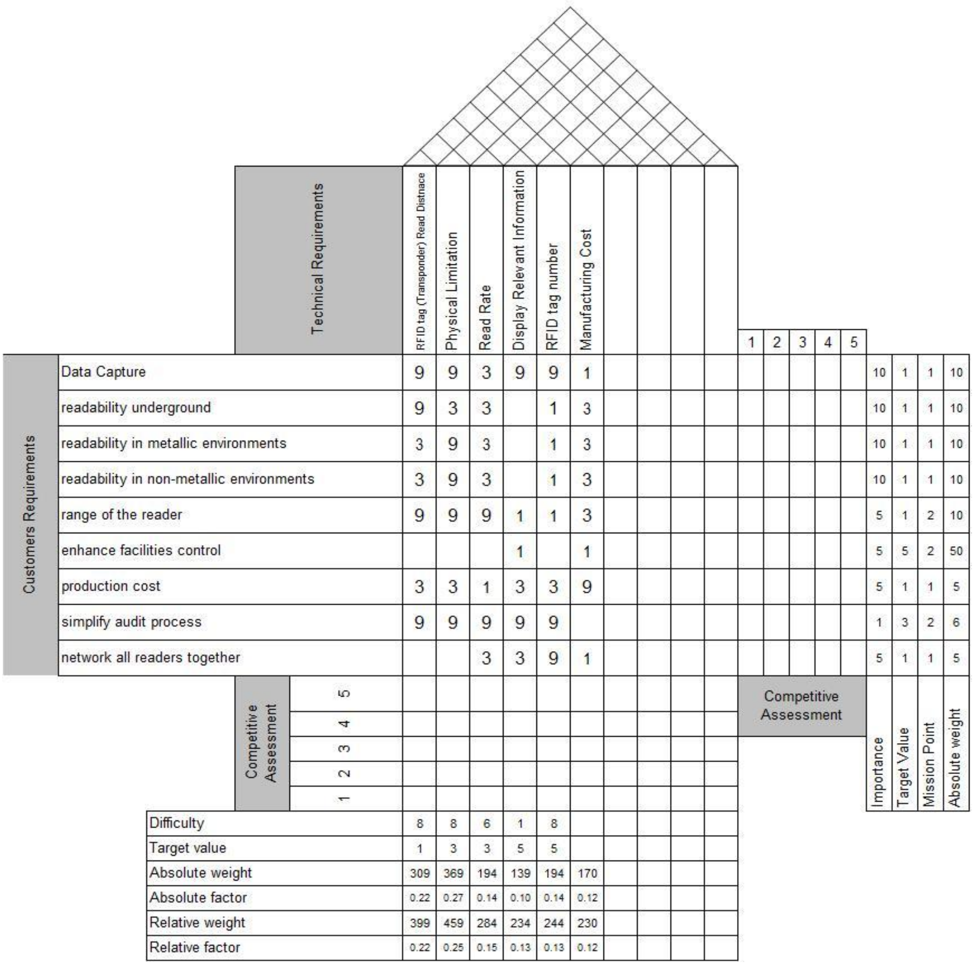

Figure 9 House of quality for all stakeholders

After collecting the stakeholder requirements, the HOQ analysis following the above procedure was performed in Figure 9, including all customers' and technical requirements. The House of Quality (HOQ) is analyzed in two ways 1) analysis of customer requirements, and 2) analysis of technical requirements.

5.1.1 Analysis of Customer Requirements

The absolute weights of customer requirements are shown in Figure 9 for the stakeholders. From the analysis by HOQ, the most important objective for these stakeholders was determined. The properties of the RFID technology the stakeholders concern were Data Capture (Customer Requirements 1), Readability Underground (Customer Requirements 2), Readability in Metallic Environments (Customer Requirements 3), Readability in Non-metallic Environments (Customer Requirements 4), Range of the Reader (Customer Requirements 5), Enhance Facilities Control (Customer Requirements 6), Production Cost (Customer Requirements 7), Simplify Audit Process (Customer Requirements 8), and Network all Readers together (Customer Requirements 9).

After defining the customer requirements, the importance, target value and mission point of each requirement were evaluated. The absolute weight of the i^{th} customer requirement was calculated by Equation 1.

In this part of the analysis, the 8^{th} customer requirement (Enhance Facility Control) had the highest absolute weight. The most important mission of the customers was the 8th customer requirement, to enhance facilities control, and this problem was addressed to improve the benefit of implementing RFID technology.

5.1.2 Analysis of Technical Requirements

The technical requirements in this case were: RFID Tag Read Distance (Technical Requirements 1), Physical Limitation (Technical Requirements 2), Read Rate (Technical Requirements 3), Display Relevant Information (Technical Requirements 4), RFID Tag Number (Technical Requirements 5), and Manufacturing Cost (Technical Requirements 6).

They were defined at the same time with the customer requirements, and then the relationship scores between the technical requirements and the customer requirements were evaluated as shown in Figure 9. The blank cells mean the score was '0'. As well, the difficulties and the target values were evaluated. The absolute weight and the absolute factor of the j^{th} technical requirement were calculated by Equation 2 and Equation 3, after evaluating the scores and calculating the absolute weights of the customers' requirements. The relative weight and the relative factor of the j^{th} technical requirement were calculated by Equation 4 and Equation 5.

Results for the technical requirements from the HOQ are shown in Table 4. From this table, the most significant technical factors for these stakeholders were determined.

Table 4 Final Evaluation from the HOQ

	Read Distance	Physical Limitation	Read Rate	Display Relevant Information	RFID Tag Number	Manufacturing Cost
Absolute Weight	309	369	194	139	194	170
Absolute Factor	0.22	0.27	0.14	0.10	0.14	0.12
Relative Weight	399	459	284	234	244	230
Relative Factor	0.22	0.25	0.15	0.13	0.13	0.12

As shown in Table 4, the most significant technical factor which may influence the implementation of RFID systems in ROW was Physical Limitation. For all uses of RFID system in transportation, it was necessary to overcome the physical limitations. The second important technical factor was Read Distance. And the lowest factor (0.12) was from Manufacturing Cost.

5.2 The Basic Quality Based Analytic Hierarchy Process

Since QFD can just be utilized to determine which factor was the most important one, and which factor was most effective to be improved to achieve the objective, some other methods should be utilized to determine which one of the existing alternatives was the best choice. In this approach, Analytic Hierarchy Process was utilized to do the decision – making analysis.

The factors in the QFD were all the attributes which should be carefully analyzed, and it was possible to use the data from QFD to AHP to get the most effective decision to identify which RFID system was the best one to be implemented.

There were four levels in the Quality based Analytic Hierarchy Process (QAHP). Level I was the overall objective, Level II was the Customers Requirements, Level III was the Technical Requirements, and Level IV was the Alternatives, which are shown in Appendix C.

The raw scores a_i' used for Level II were the absolute weights (AW_i) of each customer requirement in QFD shown in Table 5.

Table 5 Scores Utilized to Find the Pairwise Scores in the AHP

customer requirements (i)	1	2	3	4	5	6	7	8	9
AW_i (a_i')	10	10	10	10	10	50	5	6	5
normalized scores (a_i)	1.73	1.73	1.73	1.73	1.73	4.96	1.32	1.40	1.32

From Equation 20, the elements in the matrix in the form of Equation 19 were calculated shown in Table 6. Since the elements in the matrix must be integers from 1 to 9 or their reciprocals as defined by the Saaty who created AHP analysis, the elements got larger than 1 should be rounded to the nearest integer, and the elements in the symmetrical position should be the reciprocal of the integer. A sample matrix to do the analysis is shown in Table 6.

Table 6 Pairwise Scores of Customer Requirements

Customer Requirements (i)	1	2	3	4	5	6	7	8	9
Data Capture (1)	1	1	1	1	1	1/3	1	1	1
Readability Underground (2)	1	1	1	1	1	1/3	1	1	1
Readability in Metallic Environments (3)	1	1	1	1	1	1/3	1	1	1
Readability in Non-metallic Environments (4)	1	1	1	1	1	1/3	1	1	1
Range of the Reader (5)	1	1	1	1	1	1/3	1	1	1
Enhance Facilities Control (6)	3	3	3	3	3	1	4	4	4
Production Cost (7)	1	1	1	1	1	1/4	1	1	1
Simplify Audit Process (8)	1	1	1	1	1	1/4	1	1	1
Network all Readers together (9)	1	1	1	1	1	1/4	1	1	1

Following the Equation 21, the weight modulus of customers' requirements was obtained shown in Table 7.

Table 7 Weight Modulus of the Customer Requirements (*CRW_i*)

Customer requirements (i)	1	2	3	4	5	6	7	8	9
CRW_i	0.0893	0.0893	0.0893	0.0893	0.0893	0.2951	0.0856	0.0867	0.0861

From Table 7, the customer requirement which had the highest weight was the 6th (Enhance Facilities Control), and it was consistent with the absolute weight in the House of Quality.

In the same way, the matrix of the technical requirements to each customer requirement can be achieved, while the raw scores utilized were the relationship scores (CT_{ij}) in QFD. Since the relationship scores (CT_{ij}) were integers in the range between 1 and 9, they can be utilized directly to calculate the matrix. Then the weights of technical requirements to each customer requirement were obtained shown in Table 8.The weight modulus of customer's requirements had been calculated above, and then the total weights modulus of technical requirements were obtained using Equation 23. The technical requirements were in the lower level, while the customers' requirements were in a higher level. Customer requirements were more related to select the best RFID system, since who would implement RFID systems was the customer. Technical requirements were related to the overall objective through relating with customer requirements. It was more appropriate than other assigns of the levels, which would be introduced in Discussion part.

Table 8 Weights of Technical Requirements (*TRW_j*)

Technical Requirements (*j*)	Customers' Requirements (*i*)									Weight Modulus of Technical Requirements
	1	2	3	4	5	6	7	8	9	
	0.0893	0.0893	0.0893	0.0893	0.0893	0.2951	0.0856	0.0867	0.0861	
1	0.225	0.4737	0.1579	0.1579	0.2813	0	0.1364	0.2	0	**0.1447**
2	0.225	0.1579	0.4737	0.4737	0.2813	0	0.1364	0.2	0	**0.1729**
3	0.075	0.1579	0.1579	0.1579	0.2813	0	0.0455	0.2	0.1875	**0.1115**
4	0.225	0	0	0	0.0313	0.5	0.1364	0.2	0.1875	**0.2156**
5	0.225	0.0526	0.0526	0.0526	0.0313	0	0.1364	0.2	0.5625	**0.1144**
6	0.025	0.1579	0.1579	0.1579	0.0938	0.5	0.4091	0	0.0625	**0.2408**

As seen in Table 8, the technical requirement with the highest weight modulus was Manufacturing Cost, and the second one was RFID Tag Number. They were the most important factors to influence the decision-making.

Table 9 Performance of the Alternatives

	AD7	PNS1	PG21	PNS2	PNS3	PG22
Read Distance	10	8	6	4	4	3
Physical Limitation	10	9.25	6.31	4	4	3
Read Rate	10	8.67	5.67	3.67	3.67	2.67
Display information	10	10	10	10	10	10
Tag Number	10	10	10	10	10	10
Cost	105379	58280	9175	10600	6460	6910

The matrix of the alternatives to each technical requirement can also be calculated, and the raw scores were the performances of each alternative shown in Table 9 which had been graded based on the previous experiments and their costs.

Using the process shown above to achieve the AHP results, these raw scores need to be normalized by Equation 20.The manufacturing cost was an attribute which had negative influence, and was different from the others. Following the same process to calculate the weight modulus of technical requirements, the weight modulus of each alternative can be obtained shown in Table 10.

Table 10 Weight Modulus of Alternatives (AlW_l)

	Technical Requirements (j)						Weight Modulus of Alternatives
	1	2	3	4	5	6	
Alternatives(l)	0.1447	0.1729	0.1115	0.2156	0.1144	0.2408	
1	0.2656	0.2396	0.2623	0.1667	0.1667	0.0237	**0.1698**
2	0.2223	0.2225	0.2363	0.1667	0.1667	0.1102	**0.1785**
3	0.1596	0.1811	0.1585	0.1667	0.1667	0.2165	**0.1792**
4	0.1243	0.1261	0.1232	0.1667	0.1667	0.2165	**0.1607**
5	0.1243	0.1261	0.1232	0.1667	0.1667	0.2165	**0.1607**
6	0.1039	0.1047	0.0966	0.1667	0.1667	0.2165	**0.1511**

As seen in Table 10, Alternative 3 (PG21) had the highest weight modulus. The second highest weight modulus was from Alternative 2 (PNS1), and the third was from Alternative 1 (AD7).

The consistency index can be calculated based on Equation 22 and Equation 24. The ratio can be calculated using CI divided by the corresponding RI, which are shown in Table 11.

Table 11 the Consistency Analysis

	Level II	Level III	Level IV	Total
CI	0.0054	0	0.0080	
CR	0.0037	0	0.0064	0.0101

As we can see in Table 11, CR=0.0101 <0.1. It means this AHP is consistent, and the results can be accepted. Alternative 3 (PG21) was selected as the best implementation in the project. Alternative 2 (PNS1) was the second best one, and Alternative 1 (AD7) was the third best one.

5.3 Quality Based AHP with Boundaries

Since the weight modulus of alternatives obtained from above analysis of the best two alternatives had no significant difference, and there were approximate calculations when determining the matrix, an analysis for selecting the boundary of the elements was completed. As well, the shift of the weight modulus of each alternative when the pairwise scores changed in the process was attractive. The lower boundary of pairwise scores was obtained by approximating the elements which was larger than 1 to the nearest integer which was smaller than itself, and the upper boundary was obtained by approximating the elements which was larger than 1 to the nearest integer which was larger than itself. The elements in the symmetrical position were the reciprocal of the integer.

Following the same procedure shown above, the weight modulus of alternatives is shown in Table 12.

Table 12 Weight Modulus with Boundaries Utilized

Alternatives	1	2	3	4	5	6	CR
the Lower Boundary	0.2110	0.1930	0.1662	0.1465	0.1465	0.1407	0.0113
the Upper Boundary	0.2055	0.1822	0.1616	0.1431	0.1387	0.1387	0.0300

As shown in Table 12, CRs were still smaller than 0.1, so the results can be accepted. The first two best alternatives were Alternative 1 (AD7) and Alternative 2 (PNS1), while the third best was Alternative 3 (PG21). Alternative 4 (PNS2), Alternative 5 (PG22), and Alternative 6 (PNS3) were more worthless to be implemented. As well, we can see that the weight modulus of Alternative 3 (PG21) had the smallest range while changing the matrix. PG21 had the most stationary performance.

5.4 AHP with Uncertainties

In the above AHP process, the initial manufacturing cost of RFID implementation was utilized to make the decision. There were uncertainties in the

RFID market, which may influence their cost. The benefit of considering the uncertainties in the market resulted in utilized the following analysis instead of the cost.

The benefits were obtained from different models. The Decision Tree (DT) and Real Option Analysis (ROA) were utilized in this approach.

Table 13 Initial Costs for Different Types of RFID Systems

Systems	ISO/EPC Standard	R & D Cost	Trial Cost	Implement Cost
AD7	Y	\$ 1993	\$ 11793	\$ 105379
PNS1	N	\$ 5620	\$ 8020	\$ 58280
PNS2	N	\$ 6402	\$ 6450	\$ 10600
PNS3	N	\$ 3642	\$ 3690	\$ 6460
PG21	Y	\$ 2727	\$ 2775	\$ 9175
PG22	Y	\$ 1972	\$ 2020	\$ 6910

Table 14 Probabilities of Different Situations in Each Phase

	Development Phase	Trial Phase	Development Phase
Successful Results	20%	40%	30%
Fair Results	20%		
Failure	60%	60%	70%

The effective riskless interest rate per year was r=6% and the period to evaluate the risk analysis was 10 years. At beginning of the project, initial R&D costs had been invested. Then at the end of the 3rd year Trial Costs were invested, and finally, at the end of the 10th year, Implement Costs were invested in this project. All costs were shown in Table 13 for the different RFID systems. The present values of the savings (*V*) of successful RFID systems implementation were given as \$100,000 by the experts in DOT. Based on their option, the probability distribution of successful, fair and failure results are shown in Table 14.

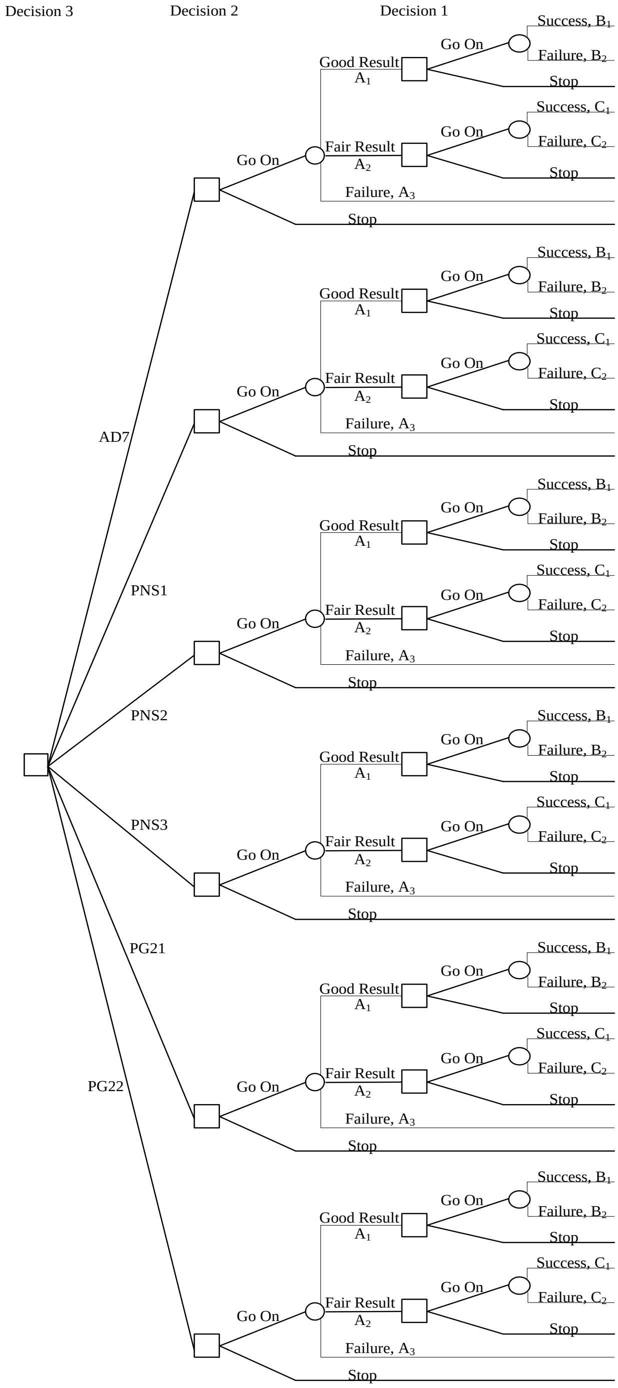

Figure 10 Decision tree developed for project

The decision tree for this project was developed in Figure 10. The expected net present values were used to determine the best RFID systems. Three decisions were made in this decision tree which runs from right to left. The square symbol indicates where a decision needs to be made. All investments need to be changed to present value utilizing Equation 6. To make Decision 1, the net present value obtained from Equation 7 or Equation 8 in the Trial Phase should be compared with no action. In order, to make Decision 2, the net present value obtained from Equation 9 in the Development Phase should be compared with no investment. Decision 3 decides which system is the most economically justified, based off the expected net present values (Table 15) and thus which one should be implemented.

Matlab® was used to simulate the model using the two main parameters of the effective risk-free rate of interest annually as r=6% and the volatility of the logarithmic rate of return as σ=27% to do ROA. These values were conservative estimate found in a R&D case study by Linwei Wei and Liangqing Yuan in Tsinghua University (Wei, L. and Yuan, L., 2004). Their study was similar to the case in this paper. The period for analysis is 10 years, so the values $t_0 = 0$, $t_1=3$, $t_2=10$ years were used. The present values of the savings (V) of successful RFID systems implementation were given as $100,000.

Following the procedures shown in Section 4.4.2 –The Compound Real Option Model, The net present value of implementing the project ($NPV=C_0$) can be obtained. The net present values of the project using the six RFID systems are shown in Table 15.

Table 15 Benefits of Different RFID Systems

Alternatives	1	2	3	4	5	6
DT	-$12488.7	-$12070.9	-$803.705	$5452.68	$6500.656	$8496.039
ROA	$39558	$56874	$89820	$82264	$89653	$92474

Replacing the costs with the benefits of all alternatives, and following the same steps above, the weight modulus of each alternative was achieved shown in Table 16.

Table 16 Weight Modulus of Each Alternative

Alternatives	1	2	3	4	5	6	CR
DT	0.1717	0.1601	0.1666	0.1652	0.1717	0.1647	0.0120
ROA	0.1672	0.1763	0.1758	0.1631	0.1631	0.1545	0.0104

As we can see, both of the Consistency Ratios (*CRs*) were less than 0.10. The AHP analysis was accepted. Using the benefit from the Decision Tree, the best alternatives were Alternative 1 (AD7) and Alternative 5 (PNS3). Both of them had the highest weight modulus 0.1717. The second best one was Alternative 3 (PG21).

Using the benefit from the Real Option Analysis, the best alternative was Alternative 2 (PNS1) with the highest weight modulus 0.1763, and the second best one was Alternative 3 (PG21) with the weight modulus 0.1758. The third one was Alternative 1 (AD7) with the weight modulus 0.1672. The results based on the benefits from different analysis were not the same as each other.

Table 17 Weight Modulus with Boundaries

Alternatives		1	2	3	4	5	6	CR
DT	Lower	0.2694	0.2467	0.2033	0.1820	0.1820	0.1747	0.0108
	Upper	0.3635	0.2796	0.2168	0.1620	0.1636	0.1336	0.0281
ROA	Lower	0.2163	0.2067	0.1714	0.1546	0.1546	0.1509	0.0094
	Upper	0.3634	0.2805	0.2167	0.1613	0.1625	0.1323	0.0299

The weight modulus with boundaries were obtained following the same steps as above. They are shown in Table 17.

As shown in Table 17, based on benefit from the Decision Tree, Alternative 1 (AD7) had the highest weight modulus not only with the lower boundary but also with the upper boundary. The second and third highest weight modulus were from Alternative 2 (PNS1) and Alternative 3 (PG21) with both the lower boundary and the upper boundary. Also, Alternative 3 (PG21) had the smallest range of the weight modulus.

Based on the benefit from the Real Options Analysis, the rank of the alternatives was the same as based on the benefit from the Decision Tree. The best three alternatives were AD7, PNS1, and PG21, for both the lower and upper boundaries. The smallest range of the weight modulus of these three alternatives was from PG21, the same as based on Decision Tree.

5.5 Comparison of Quality Based AHP with Economic Analysis

5.5.1 Decision Tree Analysis

The same values of the parameters were utilized the same as in Section 5.4 to calculate the benefits of implementing RFID systems from Decision Tree, except the values of the savings from successfully implementing different RFID systems. The present values of the savings (*V*) of successful implementation were given in Table 18, based on performance value and different implemented locations. If the implementation failed, the saving would be zero.

Table 18 Savings of Successful Implementation

Alternatives	1	2	3	4	5	6
Savings	\$100,000	\$90,000	\$62,500	\$40,000	\$40,000	\$30,000

Following the same steps of benefit calculation from DT in Section 5.4, the expected net present values of implementing different RFID systems considering the performances in different situations were shown in Table 19.

Table 19 Expected Net Present Values of Different RFID Systems

Alternatives	1	2	3	4	5	6
NPV	-\$191.68	-\$269.55	\$4373.76	-\$3796.88	\$213.71	\$1009.40

After comparison, the systems with high profit were Alternative 3 (PG21), Alternative 6 (PG22) and Alternative 5 (PNS3) from most to least profitable. These three systems were economically justified based on their positive expected net present value.

The results from the Decision Tree analysis were different from the Quality based AHP analysis. In the top three alternatives, the only overlap between both of them was Alternative 3 (PG21).

5.5.2 The Real Option Analysis

The same values of the parameters were utilized the same as in Section 5.4 to calculate the benefits of implementing RFID systems from Real Option Analysis, except the values of the savings from successfully implementing different RFID systems. The present values of the savings (*V*) of successful implementation were given in Table 18, based on performance value and different implemented locations.

Following the procedures shown in Section 4.4.2 –The Compound Real Option Model, The net present value of implementing the project ($NPV=C_0$) can be obtained. The net present values of the project using the six RFID systems are shown in Table 20.

Table 20 Net Present Value (*NPV*) of the Project

Alternatives(*l*)	1	2	3	4	5	6
NPV	\$39558	\$47599	\$52326	\$22319	\$29658	\$22497

As seen in Table 20, all systems were economically viable to be implemented in all locations. This assumption was made because the expected net present values were all positive. The system with the highest net present value was the Alternative 3 (PG21). The second one was Alternative 2 (PNS1), and the third one was Alternative 1 (AD7). All these top three alternatives were the same as the results from Quality based AHP analysis, and the only difference was the ranks of the alternatives.

Chapter 6 Discussion

In this chapter, some other possible approaches utilizing Quality Function Deployment (QFD) data into Analytic Hierarchy Process (AHP), except the basic approach introduced in the previous chapters. In the basic Quality based AHP (QAHP), there were also some limitations. Finally, the conclusions of the research are summarized.

6.1 Possible QAHP approach I

In the basic QAHP, the pairwise scores in the matrix were selected as the closest integer of the ratio. Another possible QAHP approach can utilize the original pairwise scores to obtain the results. As an example, the pairwise scores of the customer requirements were shown in Table 21 in this approach.

Table 21 Pairwise Scores of the Customer Requirements from Approach I

Customer Requirements (*i*)	1	2	3	4	5	6	7	8	9
1	1.00	1.00	1.00	1.00	1.00	0.35	1.31	1.23	1.31
2	1.00	1.00	1.00	1.00	1.00	0.35	1.31	1.23	1.31
3	1.00	1.00	1.00	1.00	1.00	0.35	1.31	1.23	1.31
4	1.00	1.00	1.00	1.00	1.00	0.35	1.31	1.23	1.31
5	1.00	1.00	1.00	1.00	1.00	0.35	1.31	1.23	1.31
6	2.87	2.87	2.87	2.87	2.87	1.00	3.75	3.53	3.75
7	0.77	0.77	0.77	0.77	0.77	0.27	1.00	0.94	1.00
8	0.81	0.81	0.81	0.81	0.81	0.28	1.06	1.00	1.06
9	0.77	0.77	0.77	0.77	0.77	0.27	1.00	0.94	1.00

Following the Equation 21, the weight modulus of customers' requirements was obtained shown in Table 22.

Table 22 Weight Modulus CRW_i from Approach I

customer requirements (*i*)	1	2	3	4	5	6	7	8	9
CRW_i	0.0979	0.0979	0.0979	0.0979	0.0979	0.2810	0.0750	0.0796	0.0750

As we can see in Table 22, the customer requirement which had the highest weight was the 6th (Manufacturing Cost), and it is consistent with the weight modulus obtained from the basic QAHP in Table 7.

In the same way, the matrix of the technical requirements to each customer requirement was achieved, while the raw scores utilized were the relationship scores (CT_{ij}) in QFD. Since the relationship scores (CT_{ij}) were integers in the range between 1 and 9, they were utilized directly to calculate the matrix. Then the weights of technical requirements to each customer requirement were obtained shown in Table 23.The weight modulus of customer's requirements were calculated above, and then the total weights modulus of technical requirements were obtained using Equation 23. The technical requirements are in the lower level, while the customers' requirements are in the higher level.

Table 23 Weights of Technical Requirements (*TRW_j*) from Approach I

	Customers' Requirements (*i*)									Weight Modulus of Technical Requirements
	1	2	3	4	5	6	7	8	9	
Technical Requirements (*j*)	0.10	0.10	0.10	0.10	0.10	0.28	0.07	0.08	0.07	
1	0.23	0.47	0.16	0.16	0.28	0.00	0.14	0.20	0.00	**0.1530**
2	0.23	0.16	0.47	0.47	0.28	0.00	0.14	0.20	0.00	**0.1839**
3	0.08	0.16	0.16	0.16	0.28	0.00	0.05	0.20	0.19	**0.1146**
4	0.23	0.00	0.00	0.00	0.03	0.50	0.14	0.20	0.19	**0.2058**
5	0.23	0.05	0.05	0.05	0.03	0.00	0.14	0.20	0.56	**0.1089**
6	0.03	0.16	0.16	0.16	0.09	0.50	0.41	0.00	0.06	**0.2339**

As seen in Table 23, the technical requirement with the highest weight modulus was Manufacturing Cost, and the second one was RFID Tag Number. They were the most important factors to influence the decision – making. And the ranking was the same as the results obtained from the basic QAHP in Table 8.

The matrix of the alternatives to each technical requirement also were calculated, and the raw scores were the performances of each alternative shown in Table 9 which had been graded based on the previous experiments and their costs.

Using the process shown above to achieve the AHP results, these raw scores were normalized by Equation 20.The manufacturing cost was an attribute which had negative influence, and was different from the others. Following the same process to calculate the weight modulus of technical requirements, the weight modulus of each alternative can be obtained shown in Table 24.

Table 24 Weight Modulus of Alternatives (AlW_l) from Approach I

	Technical Requirements (j)						Weight Modulus of Alternatives
	1	2	3	4	5	6	
Alternative(l)	0.15	0.18	0.11	0.21	0.11	0.23	
1	0.26	0.26	0.27	0.17	0.17	0.02	**0.1764**
2	0.22	0.24	0.24	0.17	0.17	0.12	**0.1840**
3	0.17	0.17	0.17	0.17	0.17	0.21	**0.1782**
4	0.12	0.12	0.12	0.17	0.17	0.22	**0.1578**
5	0.12	0.12	0.12	0.17	0.17	0.21	**0.1565**
6	0.10	0.10	0.09	0.17	0.17	0.22	**0.1471**

As seen in Table 24, Alternative 2 (PNS1) had the highest weight modulus. The second highest weight modulus was from Alternative 3 (PG21), and the third was from Alternative 1 (AD7). It was different from the result from the basic QAHP in Table 10. Shown in Table 10, Alternative 3 (PG21) had the highest weight modulus, and the second highest weight modulus was from Alternative 2 (PNS1). Because there was approximate estimation when utilizing the basic QAHP, the analysis utilizing the boundaries also shows this difference. As well, it was shown that the analysis utilizing the boundaries was necessary. Alternative 3 (PG21) was better than the other two, since it had more stationary performance by the analysis with boundaries. It was the same as the result obtained from the basic QAHP.

So the basic QAHP utilized in the previous chapters was better than the possible QAHP approach I.

6.2 Possible QAHP approach II

Another possible QAHP approach was to exchange the levels of customer requirements and technical requirements. The structure is shown in Appendix E.

It was not difficult to define the pairwise scores of the technical requirements after exchanging, and the absolute weights of the technical requirements were utilized to decide the weight modulus of each technical requirement. The pairwise scores of the customer requirements to each technical requirement were the relationship scores between the customer requirements and the technical requirements. They were the same as the basic QAHP, and the only difference was that Level II was technical requirements and Level III was the customer requirements in Approach II.

In this possible approach, the difficulty was defining the pairwise scores of the alternatives to each customer requirements. There was no direct relationship between the alternatives and the customer requirements. The technical requirements were more relative to the alternatives than the customer requirements.

So, the basic QAHP shown in previous chapter was more suitable to solve the problem.

6.3 Possible QAHP approach III

There was also a possible QAHP approach put all customer requirements and technical requirements in the same level. The structure is shown in Appendix F.

In Approach III, it was easy to obtain the pairwise scores between pairs of the customer requirements, and between pairs of the technical requirements. But the pairwise scores between one customer requirement and one technical requirement were difficult to be achieved from the QFD directly. It was challenging to define these pairwise scores, since there was no intuitive relationship between the customer requirements and the technical requirements to show which one was more important than the other.

So, the basic QAHP shown in previous chapter was more suitable to solve the problem.

6.4 Limitations

There are several major limitations in the basic QAHP analysis.

1. The basic QAHP was just one possible choice to utilize the data from QFD into AHP. It was the best result when compared to some other possible choices. The basic QAHP had not been demonstrated to be the best of all possible choices.
2. This was only one specific application of the QAHP in this research of the thesis, and it is successful. But QAHP approach has not been demonstrated to be applicable all areas.
3. It was difficult to determine whether the decision made from the basic QAHP was

definitely correct or not. It just can be concluded as it is better than the other possible approach.

4. The best alternative was obtained from the basic QAHP while it was a multi attribute decision analysis. Sometimes the best alternative obtained was not the one with a lower price. It was suspected whether the alternative obtained from the basic QAHP or the alternative with lower price should be the best implementation.
5. Since the installation costs of different RFID systems were not significantly different from each other and were difficult to estimate, this costs were assumed to have an equal impact on the selection decision.
6. The revenues and costs in each phase of the project were estimated by the experts. There were not the exact values. There may be errors when utilizing the benefits in the basic QAHP to make the decision.

6.5 Conclusions

As shown in the methodology and results, a Quality based Analytic Hierarchy Process (QAHP) was utilized to make multi-attribute decision, and it gave acceptable results.

1. Based on the kick off meetings, Quality Function Deployment (QFD) was developed. As shown, the technical requirement was physical limitation, which was the most important requirement to be achieved. If the physical limitation could be overcome, the quality of the product would have the largest improvement. The second most important requirement was Read Distance. The difference of the

relative factors between these two requirements was not large. One was 0.25, and the other one was 0.22.

Table 25 Summary of Results Obtained from Different Approaches

Alternatives (*l*)		1	2	3	4	5	6
Systems		AD7	PNS1	PG21	PNS2	PNS3	PG22
QAHP Approach I		0.1764	0.1840	0.1782	0.1578	0.1565	0.1471
Basic QAHP	Rounding	0.1698	0.1785	0.1792	0.1607	0.1607	0.1511
	Lower	0.2110	0.1930	0.1662	0.1465	0.1465	0.1407
	Upper	0.2055	0.1822	0.1616	0.1431	0.1387	0.1387
Basic QAHP with Benefits from DT	Rounding	0.1717	0.1601	0.1666	0.1652	0.1717	0.1647
	Lower	0.2694	0.2467	0.2033	0.1820	0.1820	0.1747
	Upper	0.3635	0.2796	0.2168	0.1620	0.1636	0.1336
Basic QAHP with Benefits from ROA	Rounding	0.1672	0.1763	0.1758	0.1631	0.1631	0.1545
	Lower	0.2163	0.2067	0.1714	0.1546	0.1546	0.1509
	Upper	0.3634	0.2805	0.2167	0.1613	0.1625	0.1323
DT		-\$191.68	-\$269.55	\$4373.76	-\$3796.88	\$213.71	\$1009.40
ROA		\$39558	\$47599	\$52326	\$22319	\$29658	\$22497

2. A basic QAHP approach was given. For the AHP, Level I was the overall objective – the best RFID system implemented in this project. Level II was the customer requirements, and Level III was the technical requirements in QFD. Level IV was the alternatives – six different RFID systems.

3. Since QFD gave the raw scores of every requirement, including customer requirements and technical requirements, the pairwise scores in Level II and Level III of Analytic Hierarchy Process (AHP) was obtained. After calculation, the most important factor, which had the most significant effect on the decision, was Manufacturing Cost, and the second most important factor was RFID Tag Number.

4. The most important technical requirement obtained from QAHP was different

from the result from QFD, since the meaning of the weights achieved from the two methods was different. The weights in QFD indicated that how significant the improvement of the product's quality would be if the corresponding technical requirement was improved. The weights in QAHP indicated that how significant the effect would be on the decision if the corresponding technical factor was changed.

5. The performances of different RFID systems were achieved based on the experiments and the costs were the market prices of the corresponding RFID system. Based on the performance, the cost and the weight modulus of technical requirements obtained, utilizing the basic QAHP, the best RFID system to be implemented was Alternative 3 (PG21). The second and third best systems were Alternative 2 (PNS1) and Alternative 1 (AD7) respectively. The results were accepted since $CR = 0.0101 < 0.10$ of the analysis.
6. The lower and upper boundaries were utilized in the process of calculation, and the CR was still in the accepted range. The RFID system to be implemented with the largest weight modulus was AD7. The second and third ones were PNS1 and PG21 respectively. But PG21 had the narrowest interval with the boundaries, and its weight modulus was not low. PG21 was still the best choice.
7. The benefits were replaced the costs of different RFID systems in QAHP, and the CRs were accepted. There were two approaches utilized for the benefits respectively. The decision made from QAHP using the benefits was compared

with the decision made from the corresponding economic analysis.

8. Based on Decision Tree (DT) analysis, the best implementation was PG21 with the highest profit, and the second and third ones were PG22 and PNS3 respectively. The best systems to be implemented from QAHP using the benefits of DT analysis were AD7 and PNS3. The second best one was PG21. The results were different from each other, but there was PG21 in the top three best systems from both of the analyses.
9. Based on Real Option Analysis (ROA), the best implementation was PG21 with the highest profit, and the second and third ones were PNS1 and AD7 respectively. The best system to be implemented from QAHP using the benefits of DT analysis was PNS1. The second and third best ones were PG21 and AD7 respectively. The top three best systems from both of the analysis were the same, while the ranking of the three systems was different. The results obtained from ROA were the same with the results from the basic QAHP at the beginning.
10. Through several decision-making analyses and the comparison, the basic QAHP analysis is feasible, and PG21 must be the best alternative to be implemented in the project.

Chapter 7 Contribution to the body of knowledge

The research presents a multi – attributes decision – making analysis of RFID systems implementation in ROW project. The multi-attribute analysis utilized in the thesis is Analytic Hierarchy Process (AHP), which is one of most convenience tools for the decision – making analysis. There has been the Quality Function Deployment (QFD) developed at the beginning of the project, and the data from QFD have potential to be utilized into AHP. This research shows several approaches utilizing the data of QFD in AHP to make decision, which is called Quality based AHP (QAHP). The most useful and feasible approach is selected, and treated as the basic QAHP. In addition, there are two economic analyses utilized to make decision, which RFID system has the highest profit. The basic QAHP is proved to be accepted approach through multiple comparisons. And the best RFID system to be implemented in the project is PG21.

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APPENDICE

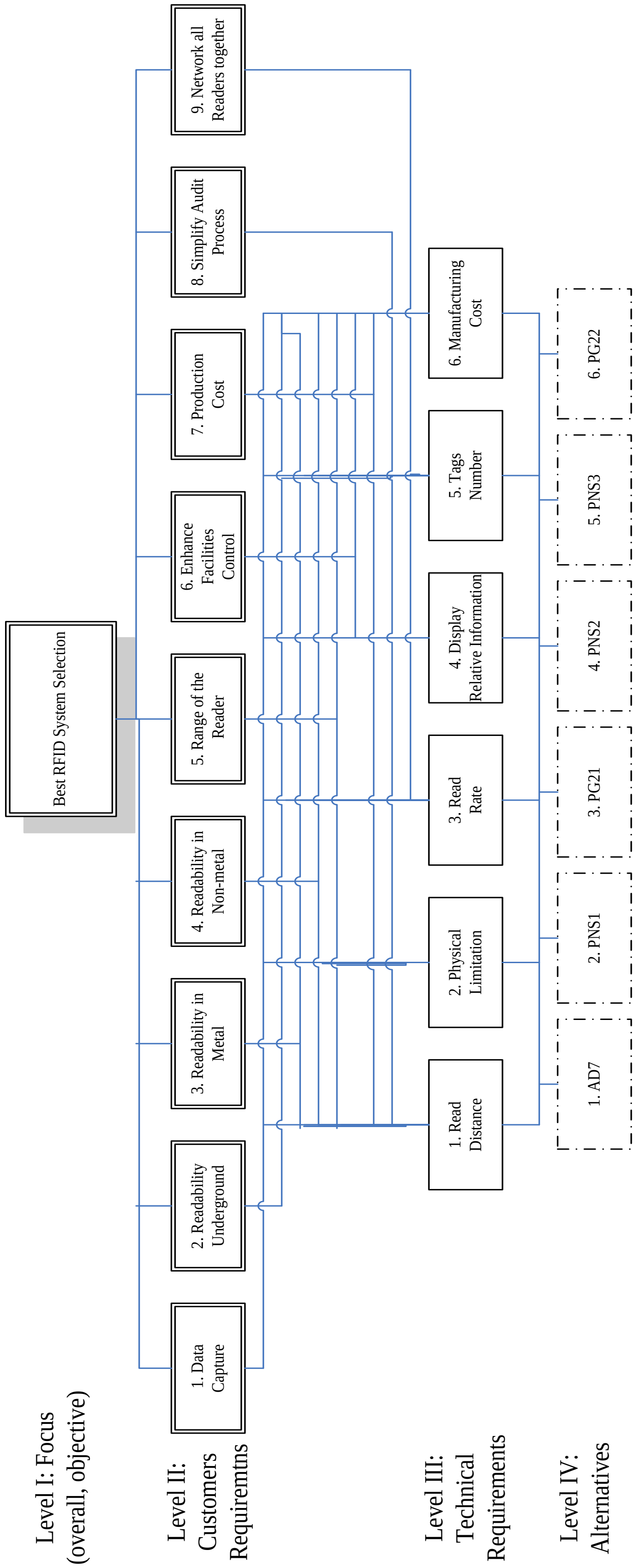
Appendix A: Acronyms Table

AD7	Active Dash 7 RFID System
AHP	Analytic Hierarchy Process
AlW	Weight Modulus of the Alternative
ANP	Analytic Network Process
AW	Absolute Weight
CI	Consistency Index
CR	Ration of CI and RI
CRW	Weight Modulus of the Customer Requirement
CT	Relationship Score between the Customer Requirement and the Technical Requirement
DOT	Department of Transportation
DT	Decision Tree Analysis
HOQ	House of Quality
i	Index for Customer Requirements
I	Importance to Customer
j	Index for Technical Requirements
l	Index for Alternatives
MP	Mission Point
NPV	Net Present Value
PE	Performance Evaluation
PG2	Passive Generation 2 RFID System
PNS	Passive Non-Standard RFID System
PS	Performance Evaluation Score
QAHP/Quality based AHP	Quality based Analytic Hierarchy Process
QFD	Quality Function Deployment
RFID	Radio Frequency Identification
RI	Random Index
ROA	Real Option Analysis
ROW	Right of Way
RW	Relative Weight
TRW	Weight Modulus of the Technical Requirement
TV	Target Value

Appendix B: Explanation of technical requirements in Quality Function Deployment (QFD)

Technical Requirements (*j*)	Explanation
RFID Tag Read Distance	the range of the reader reading the tag
Physical Limitation	the other factors which can influence the performance of the tag, such as the material the tag attached with, environments the system works in, and the angle between the tag and the reader
Read Rate	the frequency of the reader read the tag
Display Relevant Information	the ability of the reader to give useful information obtained from the tag
RFID Tag Number	number of tags needed to cover a certain area
Manufacturing Cost	costs of buying the system, based on its price

Appendix C: Structure of the basic Quality based Analytic Hierarchy Process (QAHP)



Appendix D: The Original Matrix for basic QAHP structure

Table D-1 Customer Requirements

		C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9
Customer Requirements _ Matrix	C_1	1.00	1.00	1.00	1.00	1.00	0.35	1.31	1.23	1.31
	C_2	1.00	1.00	1.00	1.00	1.00	0.35	1.31	1.23	1.31
	C_3	1.00	1.00	1.00	1.00	1.00	0.35	1.31	1.23	1.31
	C_4	1.00	1.00	1.00	1.00	1.00	0.35	1.31	1.23	1.31
	C_5	1.00	1.00	1.00	1.00	1.00	0.35	1.31	1.23	1.31
	C_6	2.87	2.87	2.87	2.87	2.87	1.00	3.75	3.53	3.75
	C_7	0.77	0.77	0.77	0.77	0.77	0.27	1.00	0.94	1.00
	C_8	0.81	0.81	0.81	0.81	0.81	0.28	1.06	1.00	1.06
	C_9	0.77	0.77	0.77	0.77	0.77	0.27	1.00	0.94	1.00

Table D-2 Technical Requirements to the 1st Customer Requirement (C_1)

		T_1	T_2	T_3	T_4	T_5	T_6
CT_{1j} _ Matrix	T_1	1	1	3	1	1	9
	T_2	1	1	3	1	1	9
	T_3	1/3	1/3	1	1/3	1/3	3
	T_4	1	1	3	1	1	9
	T_5	1	1	3	1	1	9
	T_6	1/9	1/9	1/3	1/9	1/9	1

Table D-3 Technical Requirements to the 2nd Customer Requirement (C_2):

		T_1	T_2	T_3	T_5	T_6
CT_{2j} _ Matrix	T_1	1	3	3	9	3
	T_2	1/3	1	1	3	1
	T_3	1/3	1	1	3	1
	T_5	1/9	1/3	1/3	1	1/3
	T_6	1/3	1	1	3	1

Table D-4 Technical Requirements to the 3rd Customer Requirement (C_3):

		T_1	T_2	T_3	T_5	T_6
CT_{3j} _ Matrix	T_1	1	1/3	1	3	1
	T_2	3	1	3	9	3
	T_3	1	1/3	1	3	1
	T_5	1/3	1/9	1/3	1	1/3
	T_6	1	1/3	1	3	1

Table D-5 Technical Requirements to the 4th Customer Requirement (C_4):

		T_1	T_2	T_3	T_5	T_6
CT_{4j} _ Matrix	T_1	1	1/3	1	3	1
	T_2	3	1	3	9	3
	T_3	1	1/3	1	3	1
	T_5	1/3	1/9	1/3	1	1/3
	T_6	1	1/3	1	3	1

Table D-6 Technical Requirements to the 5th Customer Requirement (C_5):

		T_1	T_2	T_3	T_4	T_5	T_6
CT_{5j} _ Matrix	T_1	1	1	1	9	9	3
	T_2	1	1	1	9	9	3
	T_3	1	1	1	9	9	3
	T_4	1/9	1/9	1/9	1	1	1/3
	T_5	1/9	1/9	1/9	1	1	1/3
	T_6	1/3	1/3	1/3	3	3	1

Table D-7 Technical Requirements to the 6th Customer Requirement (C_6):

		T_4	T_6
CT_{6j} _ Matrix	T_4	1	1
	T_6	1	1

Table D-8 Technical Requirements to the 7th Customer Requirement (C_7):

		T_1	T_2	T_3	T_4	T_5	T_6
CT_{7j} _ Matrix	T_1	1	1	3	1	1	1/3
	T_2	1	1	3	1	1	1/3
	T_3	1/3	1/3	1	1/3	1/3	1/9
	T_4	1	1	3	1	1	1/3
	T_5	1	1	3	1	1	1/3
	T_6	3	3	9	3	3	1

Table D-9 Technical Requirements to the 8th Customer Requirement (C_8):

		T_1	T_2	T_3	T_4	T_5
CT_{8j} _ Matrix	T_1	1	1	1	1	1
	T_2	1	1	1	1	1
	T_3	1	1	1	1	1
	T_4	1	1	1	1	1
	T_5	1	1	1	1	1

Table D-10 Technical Requirements to the 9th Customer Requirement (C_9):

		T_3	T_4	T_5	T_6
CT_{9j} _ Matrix	T_3	1	1	1/3	3
	T_4	1	1	1/3	3
	T_5	3	3	1	9
	T_6	1/3	1/3	1/9	1

Table D-11 Alternatives to the 1st Technical Requirement (T_1):

		Alt_1	Alt_2	Alt_3	Alt_4	Alt_5	Alt_6
Alternatives/Read Distance _ Matrix	Alt_1	1.00	1.22	1.55	2.14	2.14	2.65
	Alt_2	0.82	1.00	1.28	1.76	1.76	2.18
	Alt_3	0.64	0.78	1.00	1.38	1.38	1.71
	Alt_4	0.47	0.57	0.72	1.00	1.00	1.24
	Alt_5	0.47	0.57	0.72	1.00	1.00	1.24
	Alt_6	0.38	0.46	0.59	0.81	0.81	1.00

Table D-12 Alternatives to the 2nd Technical Requirement (T_2):

		Alt_1	Alt_2	Alt_3	Alt_4	Alt_5	Alt_6
Alternatives/Physical Limitation _ Matrix	Alt_1	1.00	1.07	1.49	2.14	2.14	2.65
	Alt_2	0.93	1.00	1.39	2.00	2.00	2.47
	Alt_3	0.67	0.72	1.00	1.44	1.44	1.78
	Alt_4	0.47	0.50	0.69	1.00	1.00	1.24
	Alt_5	0.47	0.50	0.69	1.00	1.00	1.24
	Alt_6	0.38	0.40	0.56	0.81	0.81	1.00

Table D-13 Alternatives to the 3rd Technical Requirement (T_3):

		Alt_1	Alt_2	Alt_3	Alt_4	Alt_5	Alt_6
Alternatives/Read Rate _ Matrix	Alt_1	1.00	1.13	1.63	2.29	2.29	2.87
	Alt_2	0.88	1.00	1.43	2.02	2.02	2.53
	Alt_3	0.61	0.70	1.00	1.41	1.41	1.77
	Alt_4	0.44	0.50	0.71	1.00	1.00	1.26
	Alt_5	0.44	0.50	0.71	1.00	1.00	1.26
	Alt_6	0.35	0.39	0.57	0.80	0.80	1.00

Table D-14 Alternatives to the 4th Technical Requirement (T_4):

		Alt_1	Alt_2	Alt_3	Alt_4	Alt_5	Alt_6
Alternatives/Display _ Matrix	Alt_1	1	1	1	1	1	1
	Alt_2	1	1	1	1	1	1
	Alt_3	1	1	1	1	1	1
	Alt_4	1	1	1	1	1	1
	Alt_5	1	1	1	1	1	1
	Alt_6	1	1	1	1	1	1

Table D-15 Alternatives to the 5th Technical Requirement (T_5):

		Alt_1	Alt_2	Alt_3	Alt_4	Alt_5	Alt_6
Alternatives/Number _ Matrix	Alt_1	1	1	1	1	1	1
	Alt_2	1	1	1	1	1	1
	Alt_3	1	1	1	1	1	1
	Alt_4	1	1	1	1	1	1
	Alt_5	1	1	1	1	1	1
	Alt_6	1	1	1	1	1	1

Table D-16 Alternatives to the 6th Technical Requirement (T_6) _ Manufacturing Cost:

		Alt_1	Alt_2	Alt_3	Alt_4	Alt_5	Alt_6
Alternatives/Cost _ Matrix	Alt_1	1.00	0.21	0.12	0.11	0.11	0.11
	Alt_2	4.81	1.00	0.55	0.53	0.55	0.54
	Alt_3	8.67	1.80	1.00	0.96	0.99	0.97
	Alt_4	9.00	1.87	1.04	1.00	1.03	1.00
	Alt_5	8.78	1.83	1.01	0.98	1.00	0.98
	Alt_6	8.96	1.86	1.03	1.00	1.02	1.00

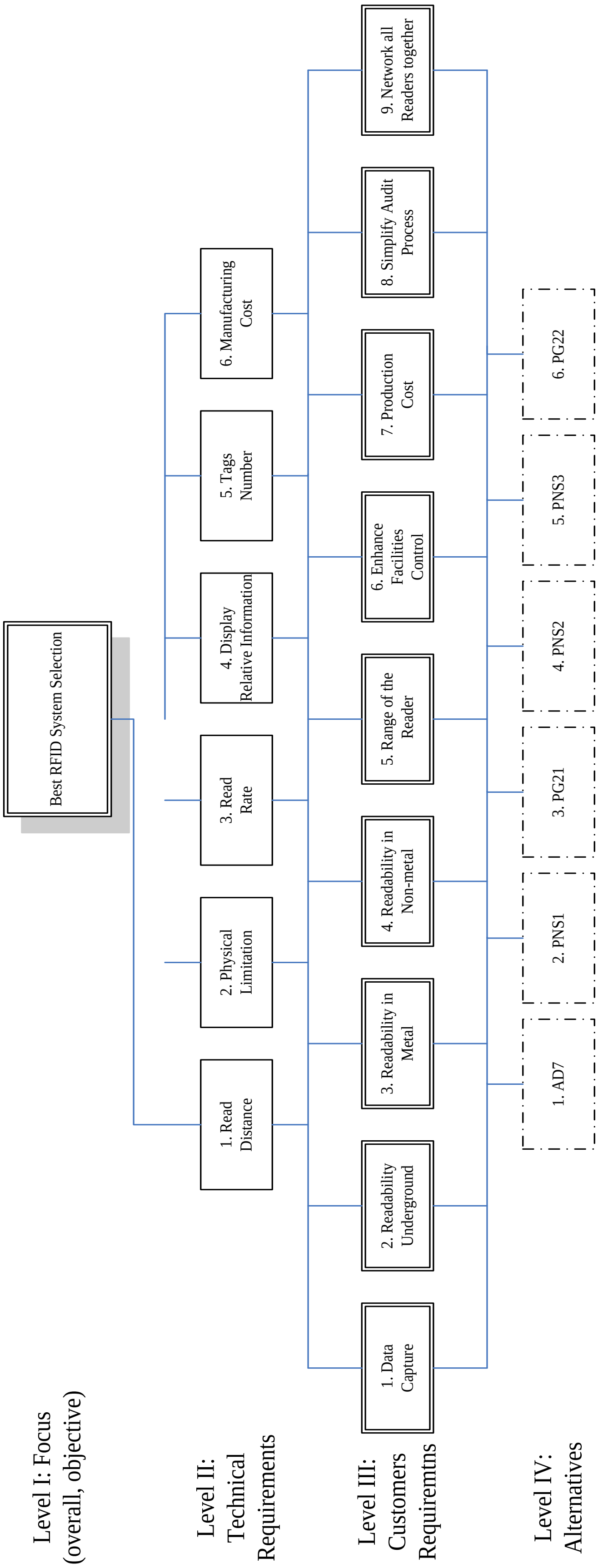
Table D-17 Alternatives to the 6th Technical Requirement (T_6) _ Benefit from Decision Tree:

		Alt_1	Alt_2	Alt_3	Alt_4	Alt_5	Alt_6
Alternatives/Benefit from DT _ Matrix	Alt_1	1.00	0.86	0.18	0.13	0.12	0.11
	Alt_2	1.16	1.00	0.21	0.15	0.14	0.13
	Alt_3	5.46	4.71	1.00	0.70	0.66	0.61
	Alt_4	7.84	6.76	1.44	1.00	0.95	0.87
	Alt_5	8.24	7.11	1.51	1.05	1.00	0.92
	Alt_6	9.00	7.76	1.65	1.15	1.09	1.00

Table D-18 Alternatives to the 6th Technical Requirement (T_6) _ Benefit from Real Options Analysis:

		Alt_1	Alt_2	Alt_3	Alt_4	Alt_5	Alt_6
Alternatives/Benefit from ROA _ Matrix	Alt_1	1.00	0.27	0.13	0.12	0.12	0.11
	Alt_2	3.65	1.00	0.49	0.43	0.42	0.41
	Alt_3	7.44	2.04	1.00	0.87	0.87	0.83
	Alt_4	8.57	2.35	1.15	1.00	1.00	0.95
	Alt_5	8.60	2.36	1.16	1.00	1.00	0.96
	Alt_6	9.00	2.47	1.21	1.05	1.05	1.00

Appendix E: Structure of the possible QAHP II



Appendix F: Structure of the possible QAHP III